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FINAL REPORT SPACE COMMUNICATIONS TECHNIQUES

PAGE COMMUNICATIONS ENGINEERS, INC.
A SUBSIDIARY OF NORTHROP CORPORATION
2011 WISCONSIN AVENUE, N.W.
WASHINGTON 7, D.C.

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285 DB

282 DB

281 DB

280 DB

SATELLITE HEIGHT 300 NAUTICAL MILES

PREPARED FOR

ROME AIR DEVELOPMENT CENTER
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
GRIFFISS AIR FORCE BASE, NEW YORK

402834

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FINAL REPORT
SPACE COMMUNICATIONS TECHNIQUES

PAGE COMMUNICATIONS ENGINEERS, INC.
A Subsidiary of Northrop Corporation
2001 Wisconsin Avenue, N. W.
Washington 7, D. C.

PCE-R-9854A

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Prepared
for

ROME AIR DEVELOPMENT CENTER
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Griffiss Air Force Base, New York

ABSTRACT

This report describes the expansion of interim simplex space communication facilities at Rome, N. Y., and Trinidad to full duplex for use in communication experiments using passive satellites. Objectives of improved tracking accuracy and system gain were achieved by providing a conical scan feed and an optical tracking system at Rome, and new cooled, low-noise doppler tracking receivers at both sites. Full duplex operation, deriving tracking information from received frequency while transmitting, and use of a highly sensitive receiving system in the same antenna with a megawatt-level radar tracking system were found practical. Tracking accuracy of the improved system proved satisfactory. Recommended improvements in the communications baseband demodulator, doppler-shift tracking, and passive radar tracking at Rome, N. Y. are discussed.

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(PCE-R-9854A, April 1963)
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PUBLICATION REVIEW

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SECTION 1 INTRODUCTION

1.1 PURPOSE

This report describes work performed by Page Communications Engineers, Inc. for Rome Air Development Center under Contract AF 30(602)-2403. The primary objective of the contract was the expansion of an interim simplex space communications facility into a full duplex facility for conducting communications experiments using passive satellites as reflectors. The facility utilizes sites near Rome, N. Y., and on Trinidad, W. I. F.

In the expansion of the facility, several measures were taken to improve tracking performance and to provide greater system gain. These improvements are detailed in the body of this report. In addition, the equipments at Floyd and Trinidad were operated and maintained during a 3-month testing period. Finally, a 60-foot X-band parabolic antenna was procured for integration with another facility located at the Floyd site.

The improved Floyd-Trinidad Space Communication Facility is described in Section 2 of this report, detailing the system parameters and describing the facilities provided at each site. Sections 3 and 4 describe experimental measurements performed with the Floyd-Trinidad Space Communication Facility. Section 3 pertains to the rf performance measurements on the system, while Section 4 details tracking system performance measurements. The 60-foot reflector and measurements performed on it are described in Section 5. Sections 6 and 7 are devoted to conclusions and recommendations. References are listed in Section 8.

1.2 EXISTING FACILITY

An existing simplex space communications facility¹ provided building blocks for the present duplex facility. The original equipment

had a capability for transmitting (a) a single voice channel, a single teletype channel, or steady tones via narrow-band frequency modulation, and (b) pulsed carrier from the Trinidad Test Site to the Floyd Test Site on a frequency of 2.27 gigacycles (gc) via an orbiting passive satellite of the Echo I type. Because of marginal signal-to-noise ratios in both the tracking and communication equipments, however, successful operation with the original system was limited to a small percentage of the passes. Degradation of the Echo I satellite had further reduced the capabilities of the system. In addition to providing duplex operation, the present system has been designed to improve tracking performance and provide increased communication-system gain. An 8-kc carrier-to-noise ratio of 20-25 db is anticipated with the Echo II satellite.

In the original system, tracking of the satellite was accomplished by a radar tracking subsystem operating on a frequency of 425 mc, utilizing the same antennas as the 2.27 gc communications signal.

The major items of equipment at the Trinidad Site were:

- a. A radar set, AN/FPT-5, operating at 425 mc.
- b. An 84-foot tracking antenna system.
- c. The transmitter portion of a radio set, AN/FRC-56, operating at 2.27 gc.
- d. A National NC1001 atomichron frequency standard.
- e. A 2-gc grid feed for use with the 84-foot antenna.
- f. Instrumentation, recording, and test equipment.

The major items of equipment at the Floyd Site were:

- a. A 33-foot tracking antenna system.
- b. A direction finding receiver system for 425-mc.
- c. A two-channel (vertical and horizontal polarization) receiver system for 2.27 gc.
- d. Instrumentation, recording, and test equipment.

A detailed description of the facility as it existed may be found in the original descriptive handbook². Under Contract AF 30(602)-2403, dated 20 January 1961, Page Communications Engineers, Inc. undertook to provide the present system.

1.3 SCOPE OF WORK

1.3.1 General

The scope of work consisted of a number of tasks as described in the succeeding paragraphs. Full details of these tasks may be found in Contract AF 30(602)-2403 and the supplemental agreements thereto.

1.3.2 2-gc Tracking System, Floyd Site

It was necessary to modify and augment the existing equipment at the Floyd Site to provide a tracking capability with an accuracy of 0.1 degree at the 2-gc data transmission frequency. This capability has been provided by installing a conical scan feed at Floyd. This feed is also capable of operating with a 10-kw transmitter operating at a frequency within 15% of the received signal frequency. A detailed description of the feed system is given in Paragraph 2.2.2 of this report.

1.3.3 2-gc Transmitter, Floyd Site

A 2-gc, 10-kw, FM transmitting capability was required at the Floyd Site for duplex operation with equipment at Trinidad. Frequency control for the transmitter was provided by a National NC1001 Atomichron frequency standard. The Floyd transmitting facility is described in Paragraph 2.2.3.

1.3.4 Optical Tracker, Floyd Site

An optical tracker having a pointing accuracy of 0.2 degree and capable of controlling the servo system of the existing 33-foot

steerable antenna was provided at the Floyd Site. Paragraph 2. 2. 5 describes this facility.

1. 3. 5 Doppler Shift Measurement, Floyd Site

The new doppler tracking receivers installed at each site utilize a phase-lock loop for tracking the received carrier. This provides a capability for measuring and recording the doppler shift of the 2-gc received signal. An accuracy of one part in 10^9 is attained by use of National NC1001 Atomichron frequency standards to derive transmitter and receiver frequency control.

1. 3. 6 2-gc Receiver, Trinidad Site

A receiving capability was installed at Trinidad to permit reception of the 2-gc signal from the Floyd Site and to complete the 2-way facility. At the same time, an identical receiving system was installed at Floyd to improve the performance of the original circuit. The receiving equipment is described in Paragraph 2. 2. 4.

1. 3. 7 Boresight Cameras

A capability was provided for photographic records of the beam alignment of the tracking antennas at both sites during optically visible satellite passes. The cameras take one photograph per second and define the dish electrical axis to within 0. 2 degree.

1. 3. 8 Primary Power, Floyd Site

The power substation at Floyd Site was augmented to provide a total capacity of:

75 kva	440 volts	3-phase
96 kva	208 volts	3-phase
20 kva	220-110 volts	single phase

1.3.9 2-gc Waveguide Azimuth Joint, Trinidad Site

A 2-gc waveguide azimuth joint assembly was devised and installed at Trinidad. This joint permits 360-degree rotation in azimuth, with positive electrical stops to prevent damage by over-rotation.

1.3.10 60-foot Paraboloidal Reflector System, Floyd Site

A 60-foot Cassegrainian paraboloidal reflector system suitable for use at frequencies in the 1.7 to 8.4-gc range was provided. The reflector system was delivered and assembled on the ground at the Floyd Site for use with another facility.

1.3.11 Maintenance and Operation

Maintenance and operation services of the communications equipment at the Trinidad and Floyd Sites were provided during periods when experiments on passive satellites were being conducted. These services were provided over a total period of three months.

SECTION 2
FLOYD-TRINIDAD SPACE COMMUNICATION FACILITY

2.1 SYSTEM PARAMETERS

2.1.1 System Description

The Floyd-Trinidad Space Communication Facility provides a 2-way communication link for space communications experiments utilizing passive satellites as reflectors. The two terminals of the link are located at the RADC Floyd Test Site near Rome, New York, and the AFMTC Down Range Tracking Station at Trinidad, West Indies. The geographic parameters of the test path are as follows:

Path Length	2085 nautical miles
Floyd latitude	43° 11.6' N
longitude	75° 20.5' W
Trinidad latitude	10° 44.3' N
longitude	61° 36.6' W

At Trinidad an 84-foot antenna is shared with the AN/FPT-5 radar which performs the tracking. At the Floyd Site a 33-foot antenna is used with three selectable tracking modes. The two radio tracking modes provide passive tracking on either the 425-mc radar signal or the 2.27-gc communication signal from Trinidad. A third tracking mode permits optical tracking of a visible satellite during periods when cloud cover permits.

Essentially identical transmitting and receiving facilities are installed at each site. The radio parameters of the system are listed below.

Transmitter power	10 kw
Transmitter frequency	
Floyd	1.84 gc
Trinidad	2.27 gc

Baseband width	4 kc
RF bandwidth	8 kc
Modulation type	nbfm (deviation ratio = 1) (both directions) pulse (Trinidad to Floyd only)
Receiver noise figure	1.25 to 1.75 db

Although the Floyd-Trinidad Space Communications Facility was designed to operate with the Echo I satellite, it also provides usable signals by lunar reflection. Computed performance of the system with the Echo I and Echo II satellites and with the moon is described in the following sections.

2.1.2 Satellite Visibility

For a satellite at specified altitudes, areas of mutual visibility can be computed as a function of distance between observers. Any satellite in these areas will be within radio line-of-sight from both ground stations.

In an operating system, communication via a satellite may not be practical for elevation angles near the horizon because of the effects of the atmosphere and ground on radio wave propagation. Atmospheric scintillations also may make accurate tracking of the satellites difficult at low angles. In addition, the temperature seen by the antenna rises sharply at low angles, due to increased oxygen and water vapor absorption and illumination of the ground by antenna side lobes. For these reasons, an angle of 8° has been taken as a minimum elevation angle in the computations which follow.

For circular orbits, the minimum allowable elevation angle and the satellite orbital height define a circle of visibility centered on each terminal site. For a given satellite height, if the circles of visibility of any two stations overlay, the overlapping areas define a region of mutual visibility between those two sites. For the Floyd-Trinidad facility, the areas of mutual visibility for the 900-nautical-mile Echo I satellite and the 650-nautical-mile Echo II satellite are shown in Figure 2-1.

2.1.3 Path Loss

The path loss between an isotropic antenna on the earth and an isotropic passive satellite will be primarily the free-space loss, plus some additional losses due to the attenuating effects of the troposphere and ionosphere.

The free-space path loss L_p of a passive satellite system may be expressed by the basic radar equation:

$$L_p = \frac{P_t}{P_r} \left[\frac{4\pi R_1^2}{g_t} \right] \frac{1}{A_s} \left[\frac{4\pi R_2^2}{A_r} \right] \quad (1)$$

where:

- P_t = transmitted power
- P_r = received power
- R_1 = distance from site 1 to satellite
- R_2 = distance from satellite to site 2
- g_t = transmitting antenna gain referred to an isotropic antenna
- A_s = effective reradiating area of the satellite
- A_r = effective area of receiving antenna = $\frac{\lambda^2 g_r}{4\pi}$
- g_r = receiving antenna gain referred to an isotropic antenna
- λ = wavelength.

For a spherical satellite whose diameter is large compared with a wavelength, the effective reradiating area is independent of the angle between the incident and scattered path and is given by:

$$A_s = \frac{\pi D_s^2}{4} \quad (2)$$

where D_s is the diameter of the sphere. Making use of this relationship, Equation (1) can be rewritten:

$$L_P = \frac{4^4 \pi^2 R_1^2 R_2^2}{\lambda^2 D_s^2 g_t g_r} \quad (3)$$

A plot of Equation (3) for $g_t = g_r = 1$ is shown in Figure 2-2 for a 100-ft. diameter passive satellite. The loss varies inversely as the square of the diameter of the sphere, which expressed in decibels and referred to a 100-ft. diameter sphere is $20 \log \left(\frac{D_s}{100} \right)$, so the curve may be used for other satellite diameters by applying the following corrections:

Diameter, D_s ft.	Loss Correction (db)
12	+18.4
32	+ 9.9
100	0
135	- 2.6
316	-10
1000	-20

In addition to the free-space loss calculated above, consideration must be given to the additional effects of attenuation due to oxygen and water vapor in the troposphere.³ These losses decrease sharply as the elevation angle relative to the horizon increases. For the Floyd-Trinidad path and for an 8-degree minimum angle of elevation, these losses will be small--probably always less than 1 db. Signals propagated via low-angle paths to and from the satellite involve a very small probability of additional attenuation (at 2 gc) of up to 2 or 2.5 db because of scattering attenuation in extended zones of very heavy rainfall, snow, ice crystals, or hail within the beam. There will also be a moderate increase in the noise level when the receiving antenna is looking into such storm regions.

2.1.4 Path Loss Profiles

Based on the path loss computed from the radar equation, it is possible to plot path loss contours or geographic lines of constant path loss for satellite

communication. These constant-loss contours are calculated, as described in Appendix A, for a particular satellite height and include all geometric effects including earth curvature. On the Floyd-Trinidad circuit, path loss contours are plotted for the 900-mile-high Echo I satellite in Figure 2-3, and for the 650-mile Echo II satellite in Figure 2-4. Those portions of the contours which are further restricted by the requirement that the satellite be visible from both sites and at an elevation of at least 8° are not shown.

The constant-loss contours show a narrowing in the middle, which illustrates the well-known fact that the efficiency of passive repeaters increases as the reflector approaches the transmitting or receiving site.

An area of radio visibility may be defined as the area obtained by the simultaneous consideration of the geometric and the radio-system gain factors. The area of radio visibility, for example, for a system having a 280-db gain is the area inside the 280-db contour which also falls inside the area of mutual visibility defined by the aforementioned geometric considerations. An analysis of this type amounts to a simultaneous solution of equations involving both the radio and geometric considerations of visibility.

Two relationships are fairly evident from examination of Figures 2-3 and 2-4. The first is the extreme sensitivity to system gain evidenced by the variation in area of the constant-gain contours. In fact, the variation of 1 db in system gain, in some cases more than doubles the useful area falling inside the region of mutual visibility. The second item of interest is the observation that, to fully utilize any satellite placed in orbit, the system gain should be sufficient for the gain contour to include all of the area inside the region of mutual visibility.

2.1.5 Antenna Beamwidth and Pointing Considerations

The choice of antenna size and transmitter power for a communications system is usually determined by the most economical combination available that will give the required system gain. In satellite communications, these factors remain important, with additional requirements in the following areas:

- (a) Antenna beamwidth must be somewhat greater than the probable error in tracking.
- (b) Antenna beamwidth must not be so narrow that signals will be greatly affected by refraction in the troposphere and ionosphere. Refractive scintillations would result in severe fading of the signal.
- (c) The antenna mount must be capable of rotating the antenna at angular velocities and accelerations sufficient to track the satellite.

The effects of atmospheric refraction become increasingly important at low elevation angles. For a minimum elevation angle of 8° , the effects of atmospheric and ionospheric refraction are estimated⁴ to be less than 0.1° above 1 gc. Considering these factors, an antenna beamwidth of 0.2° may be considered a practical minimum.

The Trinidad 84-foot diameter parabolic reflector approaches this limit in the frequency range under consideration. To the extent that the tracking and servo systems are unable to follow angular variations of the received signal due to atmospheric scintillations, an allowance would have to be made in system gain for the effects of pointing inaccuracy introduced in this manner if the antenna were appreciably larger. It is not anticipated that with the beamwidth of the Trinidad antenna, any appreciable degradation will result from this effect. Since the Floyd antenna beamwidth is even greater, its pointing error also introduces negligible degradation.

2.1.6 Noise Considerations

Before discussing the specific receiving system installed, it is desirable to consider the effect of the low sky-noise encountered at microwave frequencies. It can be seen that the use of receiver noise figure alone is not fully satisfactory at these frequencies, as noise figure is referenced in terms of a somewhat arbitrary constant-room-temperature thermal noise. As actual microwave sky temperatures may be much lower, it is evident that realized sensitivity may be much better than is indicated by consideration of receiver noise figure alone.

A more practical indication of system sensitivity is to be had through the concept of effective system temperature, T_s , defined as follows:

$$T_s = T_r + T_c + T_b + T_a, \quad (4)$$

where:

$T_r = T_o (F-1)$, is the effective receiver noise temperature,

T_o is the ambient thermal noise temperature (290°K),

F is receiving system noise figure, expressed as a power ratio,

T_c is temperature of cosmic noise,

T_b is the noise temperature associated with the contribution of the earth due to antenna side and back lobes, and

T_a is the noise temperature due to atmospheric attenuation.

Typical values of the last three components have been given by Hogg⁵ as: $T_c = 5^\circ\text{K}$ at 2 gc, $T_b = 20^\circ\text{K}$ (measured at 10 gc but probably representative at 2 gc), and $T_a = 15^\circ\text{K}$ at 8° elevation above the horizon.

Assuming these values to be fixed and representing all the external noise, one may now calculate overall system temperature as a function of the receiving system noise figure. Receiving system noise figure here includes line and duplexer loss for the case when these components are also at 290°K.

$F(\text{db})$	$T_r (^{\circ}\text{K})$	$T_s (^{\circ}\text{K})$	System Sensitivity Relative to Perfect Receiver (db) $10 \log_{10} [T_s / (T_s - T_r)]$
5	627	677	12.3
4	438	478	10.8
3	289	329	9.2
2	170	210	7.2
1	75	115	4.6
0	0	40	0

From the above table it is evident that at low noise figures an improvement in system sensitivity can be realized that is substantially greater than the actual reduction in receiver noise figure. This emphasizes the importance of maintaining the lowest possible receiver noise figure.

The system as presently installed utilizes parametric amplifiers which yield a receiver noise figure of 1.25 to 1.75 db. An additional 0.75 db of duplexer and line losses yields a receiver noise temperature of approximately 200° K and an overall effective system temperature of about 250°K. This represents an improvement of approximately 4 db over the 615°K system temperature of the interim 4-db noise-figure parametric amplifiers.

2.1.7 System Performance.

With a knowledge of the satellite communication system gain, reference to the communications gain profiles (Figures 2-3 and 2-4) will permit the

determination of regions within which the satellite must be situated to permit communication. The system parameters which define the communication gain of the Floyd-Trinidad facility are as follows:

Transmitter power	10 kw
Carrier frequency (2 gc nominal)	2.27 gc Trinidad to Floyd 1.84 gc Floyd to Trinidad
Trinidad antenna diameter	84 feet (G = 52.0 db)
Floyd antenna diameter	33 feet (G = 44.8 db)
Receiver noise figure	1.5 db
Receiver IF bandwidth	8 kc
Total line and duplexer losses (2.0 db nominal)	3.0 db Trinidad to Floyd 1.1 db Floyd to Trinidad
Atmospheric absorption	0.5 db
Required received s/n ratio	12.5 db (predetection)
Atmospheric, cosmic, and sidelobe temperature	40°K

Based on the above parameters, the system gain of the Floyd-Trinidad facility is 286.4 db computed as follows:

Transmitter power	(+) 40.0 dbw
Trinidad antenna gain	(+) 52.0 db
Floyd antenna gain	(+) 44.8 db
Line and duplexer losses	(-) 2.0 db
Atmospheric absorption	(-) 0.5 db
Desired S/N	(-) 12.5 db
Conical scan loss (Trinidad-to-Floyd only)	(-) 0.5 db
Receiver noise level*	(-) -165.6 dbw
Total system gain	286.9 db

* Receiver noise level = $K T_s B = 10 \log B + 10 \log T_s - 228.6 \text{ dbw}$

10 log B	(+)	39.0 db	(B = 8 kc)
10 log T _s	(+)	24.0 db	(T = 250° K)
Noise per cycle at 1° K		-228.6 dbw	
Receiver noise level		-165.6 dbw	

By reference to Figures 2-3 and 2-4 it can be seen that the Floyd-Trinidad facility yields the required signal-to-noise ratio (12.5 db, IF) with the following margins:

<u>Condition</u>	<u>Margin</u>
Echo I satellite, most favorable position	7 db
Echo I satellite, least favorable position	1 db
Echo II satellite, most favorable position	14 db
Echo II satellite, least favorable position	9 db

It should be pointed out that the communications gain profiles were computed for a frequency of 2 gc, intermediate between the two frequencies (1.84 gc and 2.27 gc) used for transmission in opposite sections on the Floyd-Trinidad path. As demonstrated by Equation (3), the free-space path loss between isotropic antennas varies as the square of the transmitted frequency. Since constant-aperture antennas are used at each terminal, the total antenna gain is also a function of frequency, varying as its fourth power. The net result is a variation of system gain with the square of the transmitted frequency. This results in a correction of approximately 1 db between the system performance computed for the 2-gc nominal frequency and that which results at either of the frequencies actually used. This small correction is approximately balanced by the difference in line losses between the reverse paths, which have also been taken at their average value, 2 db. The path-loss contours given, therefore yield correct answers for either frequency, when used with the stated average systems parameters.

2.2 FLOYD FACILITY

2.2.1 Site Description

The northern terminal of the experimental passive satellite communications facility is located at the RADC Floyd Test Site, 5 miles east of Griffiss Air Force Base, New York. The site includes a 33-foot tracking antenna and the three inter-connected buildings which house the tracking and communications equipment. An optical tracker is located about 700 feet northwest of the buildings and antenna. The interior of the three interconnected buildings is divided into four rooms as follows:

- Operations and receiving equipment room
- Transmitter Room
- Office
- Shop

Figure 2-5 is a plot plan of the RADC Floyd Test Site.

A block diagram of the Floyd installation is shown in Figure 2-6. As indicated, the principal subsystems are antenna, transmitting, receiving, tracking, and instrumentation equipments. These equipments are described in the paragraphs which follow, and a list of major items of equipment at the Floyd site is provided in Appendix B.

2.2.2 Antennas and Transmission System

2.2.2.1 Antenna Description. The antenna at the Floyd site has provisions for passive tracking at both the radar and communications frequencies. The feed complex is clustered at the focal point of a 33-foot-diameter paraboloidal reflector with an F/D ratio of 0.425.

It is made up of a waveguide feed network of four dual-polarized feedhorns for the frequencies 1.84 gc and 2.27 gc. Four 425-mc spiral antennas are arrayed about the center feed, and their outputs are combined to yield monopulse tracking information.

The communications (2-gc) feed network provides a horizontally polarized on-axis beam for transmission and two conically scanning receiving frequency beams. One of the receive frequency beams is vertically polarized, and the other receives horizontally polarized signals. The conical scan is synthetically generated, and individual channel control is provided to allow the two receiving beams to produce in-phase error signal information. Figure 2-7 shows the four-port feed with the phase centers of each port aligned on the diagonals of a square. All the interconnecting transmission lines are formed in WR-430 aluminum waveguide. Each of the four feedhorns has two output ports; a rear port for the horizontally polarized signals and a side port for the vertically polarized signals. The feed network thus provides four separate outputs for each polarization, which are combined to produce a sum arm and a composite difference arm for each channel. Since both the vertical channel and the horizontal channel are electrically the same, the remainder of the discussion will be limited to a single channel of operation.

2.2.2.2 Theory of Operation. The operation of the Floyd communications frequency antenna feed is best introduced by reference to Figure 2-8. This sketch shows a four-antenna cluster with the antennas arranged in diamond fashion to form an azimuth pair (No. 2 and No. 4) and an elevation pair (No. 1 and No. 3). At each of the four antenna outputs, a dual-polarization transducer is introduced which allows horizontally- and vertically-polarized signals to be processed with separate, but identical, feed networks.

When a signal is introduced into either of the difference channels at C, the signal divides evenly between the respective hybrid pair located at points A and A'. The signal out of the hybrid at A' causes antenna No. 1 to have a relative excitation coefficient of e^{j0} , and causes antenna No. 3 to have a relative coefficient of $e^{j\pi}$. The 90-degree phase shift between points C, and the difference channels of the hybrids at A, causes antenna apertures No. 2 and No. 4 to have excitation of $e^{j\pi/2}$ and $e^{j3\pi/2}$, respectively. This progressive phase-equi-amplitude distribution establishes the desired difference modes.

When a signal is introduced into either waveguide Tee at points B, the power divides evenly between the sum arms of the hybrids of A and A'. The two hybrids then jointly excite all four apertures with equal phase and equal amplitude. This equiphase-equi-amplitude excitation will be recognized as the familiar sum mode distribution.

The relative phase between the sum and difference inputs at points D is varied by means of a rotary phase shifter inserted in the difference line. The difference output is then routed from the terminal of the variable phase shifter into one of the shunt arms of a variable power divider. The sum energy is correspondingly routed to the second arm of the two-way variable power divider. The output of this power divider is then connected to the tracking receiver through a triple-stub tuner and receive frequency filter. The following paragraphs will discuss the way in which the synthetic conical scan can be controlled by the variable phase shifter, while the crossover level can be independently controlled by the power divider at D.

It will be shown in the succeeding paragraphs that the total relative pattern of the difference channel prior to D may be represented by the expression

$$E_{\Delta}(\theta, \phi) = e^{j(\phi + \beta)} \sin^2 k_1 \theta, \quad (6)$$

where:

θ and ϕ are the angular space coordinates, as shown in Figure 2-9, k_1 is a constant which determines the beamwidth of the antenna pattern, and β is the phase shift introduced by the variable phase shifter.

Equation (6) indicates that the pattern amplitude is invariant with ϕ , being a function of θ only. The phase, however, is linear with ϕ , traversing 360 electrical degrees for one revolution about the boresight axis. In any plane cut through the boresight axis, the pattern is sinusoidal in form with a phase inversion as the angle passes through the boresight axis. Typical θ and ϕ patterns for both phase and amplitude are shown in Figure 2-10. The beam maximum in the θ plane is θ'_{μ} , and is dependent on the off-boresight angle of the feed channels and the illumination of the paraboloidal.

The sum pattern, can be shown to be of the form

$$E_{\Sigma}(\theta, \phi) = \cos^2 k_2 \theta, \quad (7)$$

where k_2 is a constant which determines the beamwidth.

Equation (7) indicates that the sum pattern has a maximum on-axis and that both the phase and amplitude are independent of ϕ .

When the two signals are combined through the variable power divider, the resultant voltage pattern becomes

$$E_D(\theta, \phi) = G_{\Sigma}(A_{\Sigma}) \cos^2 k_2 \theta + e^{j(\phi + \beta)} G_{\Delta}(1 - A_{\Sigma}) \sin^2 k_1 \theta, \quad (8)$$

where: G_{Σ} and G_{Δ} are the maximum gains for the Σ and Δ channels, respectively, and

A_{Σ} is the normalized current excitation of the sum channel at D.

Examination of Equation (8) will indicate that, for a given offset angle θ , the maximum occurs where β is equal to θ , and the minimum occurs where $\beta = \theta + \pi$. It is further evident that the signal is modulated as a target revolves (at a fixed angle θ) about the boresight. The modulation ratio can be derived from Equation (8) as

$$E(\theta) = \mu \cos(\beta - \theta), \quad (9)$$

where μ is the modulation ratio

$$\mu = 1/2 \frac{G_{\Sigma} A_{\Sigma} \cos^2 k_2 \theta}{G_{\Delta} (1 - A_{\Sigma}) \sin^2 k_1 \theta} \quad (10)$$

For the plane containing the beam maximum ($\beta = \theta$), the location of the pattern maximum is defined by the transcendental expression

$$k_2 G_{\Sigma} A_{\Sigma} \sin^2 k_2 \theta_{\mu}'' = k_1 G_{\Delta} (1 - A_{\Sigma}) \sin^2 k_1 \theta_{\mu}'', (\beta = \theta \text{ plane}), \quad (11)$$

where θ_{μ}'' is the pattern maximum of the conically-scanning beam.

Figure 2-11 (a) is a sketch of the conical-scan pattern in the $\theta = \theta$ plane. The ratio of the beam maximum to the crossover level is controlled by the variable power divider, which controls the magnitude of A_{Σ} . The modulation of the pattern for angular positions about the boresight axis, for a constant offset θ_{μ}'' , is shown in Figure 2-11 (b) as given by Equation (9).

Equation (9) completely defines the position of a target relative to boresight. The off-boresight angle of a target (θ_T) is fully defined by the modulation ratio. The azimuth and elevation errors are $\cos\beta$ and $\sin\beta$, respectively, which are the readout parameters of the two-phase reference generator (see Figure 2-18). Figure 2-12 describes the target position in terms of the coordinates θ and ϕ .

2.2.2.3 Communications-Frequency Feedhorn and Transducer. A major component of the feed network is the four-channel, eight-port feedhorn and transducer. This item is pictured in Figure 2-13. There are four channels for vertical polarization (end ports) and four channels for horizontal polarization (side ports). The isolation between the horizontal and vertical inputs is a minimum of 30 db, and an average of greater than 35 db, across the 1.7 - 2.4 gc band. The full-band input mismatch is less than 1.4 to 1 for all eight ports. The aperture opening is six and one-eighth inches square. Ridge loading in the horn aperture was utilized in order to allow propagation in the lower portion of the frequency band. A sealed radome protects the feed interior from foreign matter and allows pressurization of the network. The feed is of all aluminum construction with continuous weld seams to prevent leakage. The total weight of the assembly is 19.5 pounds, including the weight of the eight standard aluminum flanges.

2.2.2.4 Sum and Difference Hybrids and Fixed 90-degree Phase Shifters. The sum and difference hybrids establish the desired modes of the feed system and are therefore key items. These components maintain the sum and difference output phases within ± 2 degrees over the full guide band, and the power division is equal within ± 0.1 db. The difference port mismatch is less than 1.36 to 1 over the full frequency band, while the sum port has a mismatch of less than 1.38 to 1 over the band. The isolation is a minimum of 33 db between the sum and difference ports.

It was noted earlier that a 90-degree phase shift is required between two hybrid difference ports in order to establish the required progressive phases in the difference mode. The Floyd feed utilizes a waveguide-type broadband phase shifter with the differential phase shift achieved by varying the broad dimension of the waveguide wall. The phase shift is controlled to less than ± 3 degrees over the full waveguide band.

2.2.2.5 Rotary Phase Shifter. It was shown in the discussion outlining the theory of operation, that the synthetic conical scan is controlled by a continuous rotary phase shifter. The dual-channel phase shifter utilized is based on the technique described by Fox.⁶ The theory of operation for this device is well known and will not be repeated here. This type of phase shifter consists of a rotating half-wave section sandwiched between two fixed in-line quarter-wave sections. The phase shift, θ , is exactly equal to twice the mechanical rotation of the half-wave polarizer. Hence, to achieve the 28.75-cps scan rate, the rotary section rotates only at a 14.37-cps rate (850 rpm). Although Fox's original phase shifter used thin dielectric plates to realize a phase shift between two orthogonal polarizations, the Floyd unit utilizes metallic irises oriented at 45 degrees relative to the input E-vector. The choice of irises as opposed to dielectric plates results in a broadband unit which is mechanically very rugged. Since the rotary phase shifter is in the receive line, it was possible to use mode-suppressing resistive cards without fear of power failure.

Figure 2-14 is an interior view of the two-channel rotary phase shifter. The rotating half-wave sections are driven by a common motor rotating at a speed of 1700 rpm. The input and output quarter-wave sections are terminated in WR-430 waveguide, and are sealed to the housing with a continuous weld. The two-phase reference generator, utilized to provide the azimuth and elevation error voltages, is directly coupled to the motor. The scan frequency reference voltages are in the form of a 28.75 cps modulation on a 400-cps carrier. The 400-cps generator is shown sandwiched between the two channels.

Access to the power and error voltage leads is through an eight-prong sealed plug located on the side of the housing. The entire package is capable of pressurization, and all components are made accessible by removing the top cover, which is gasket-sealed to prevent leakage. The assembly is mounted on one-half-inch aluminum plate so that the operation of the phase shifter be unhindered by antenna vibration. The electrical performance of the phase shifter is as follows:

Frequency range	1.7 - 2.4 gc
Phase shift errors (tuned)	± 1 degree maximum
Phase shift errors (untuned)	± 5 degrees maximum (approximate)
Insertion loss	0.2 db maximum tuned, 0.5 db maximum untuned
Wow	± 0.1 db tuned, ± 0.25 db untuned
Channel tracking errors	± 5 degrees maximum
VSWR	1.25 maximum tuned, 1.5 maximum untuned.

Tuning screws are provided for fine adjustment of the phase shifter, which is presently aligned for the 2.27 gc Floyd receive frequency.

The gears driving the half-wave sections for both channels are adjustable, in order that the scanning beams for both polarizations may be coincident. The reference generator is also adjustable, thus allowing for proper orientation of the azimuth and elevation planes.

2.2.2.6 Variable Power Divider. The sum and difference ports are interconnected at the variable power divider. Adjustment of this component allows the crossover level to be adjusted to the desired value. A crossover level of 0.5 db is presently in use. Figure 2-15 is a photograph of the power divider utilized in the Floyd feed. The component is simple in concept, being basically nothing more than an E-plane series junction with a movable center vane. The

position of the vane is controlled by the rotary shaft which can be seen in the photograph. Although the power divider is not a sophisticated component, it has the advantage that the power division is (theoretically) independent of frequency. The pictured power divider has an input mismatch of less than 1.3 for all band frequencies and for any position of the vane.

2.2.2.7 2-gc Transmission System. In addition to standard waveguide components and the special components in the feed system such as magic tees, fixed and rotary phase shifters, and power dividers, each receiver line has a three-stub tuner, a receive frequency bandpass filter, a directional coupler for insertion of test signals, a waveguide-to-coax transition, and a short length of RG-17/U Coaxial cable. The transmit line has a three-stub tuner, a flexible section of waveguide section 28 feet long to achieve ± 540 degrees of azimuth rotation, and an absorption-type low-pass filter to suppress harmonics generated in the power amplifier.

2.2.2.8 Duplexer. A duplexer or branching filter is included in the waveguide leading to the vertically polarized on-axis feed. This branching filter, which consists of sharply tuned receiver band and transmitter band filters and a common junction between filters and antenna, permits simultaneous transmission and reception without interference, through a common feed line. The filters are constructed of WR-430 waveguide with inductive irises and capacitive tuning screws forming in-line resonant cavities, four of which are used in each filter arm. A transmit-frequency rejection of over 100 db is provided in the receiver arm while the transmitter arm has a receive-frequency rejection of over 80 db. The receive filters inserted in the two receiver lines are of the same direct-couple cavity construction as the duplexer filter arms.

The duplexer is mounted in the RF equipment shack on the back of the parabolic reflector and moves with the dish. In this way any receive-frequency

noise generated in the flexible waveguide during antenna movement will be rejected by the transmit arm of the duplexer. Location of the duplexer on the rear of the dish also permits the parametric amplifiers to be mounted on the back of the reflector, keeping the receive transmission lines as short as possible. This contributes to the maintenance of an absolute minimum receiving system noise temperature.

2. 2. 2. 9 425-mc Feed System. The radiation system components to provide radar frequency tracking signals are four spiral antennas and four printed circuit ring hybrids. The four spiral antennas are clustered about the focal point of the paraboloid as shown in Figure 2-16. The spiral feed elements provide the capability of reception of linearly polarized signals of any orientation. Since the path geometry did not permit control of the received-signal polarization, this approach was required to provide full-time tracking capability with single elements.

The antenna elements feed the ring hybrids to provide the standard three-channel monopulse outputs, a sum channel, an azimuth difference channel, and an elevation difference channel. There are no provisions for transmission at this frequency, and the three information channels are fed through coaxial lines to the receiving equipment mounted in the structure on the rear of the dish, where the tracking signal is processed.

2. 2. 2. 10 Performance. Significant performance characteristics of the Floyd antenna and transmission system at 2 gc are as follows:

Antenna gain	44.8 db
Antenna H-plane beamwidth	55'

Antenna E-plane beamwidth	1° 18'
Transmission system loss, feed to horizontal receiver input	1.1 db
Transmission system loss, feed to vertical receiver input	0.8 db
Transmission system loss, transmitter to feed	1.1 db
Antenna Temperature including feed-line and filter losses (above 8° elevation)	130°K
Conical scan crossover level	-0.5 db

2.2.3 Transmitting Equipment.

A 10-kilowatt FM transmitting facility is provided at the Floyd site. The transmitting equipment consists of an AN/FRC-56(V) power amplifier utilizing a Varian VA800 Klystron and a REL type 867C exciter. The exciter is similar to the AN FRC-56(V) exciter, but is designed to operate with an external frequency synthesizer. The Floyd transmitting frequency of 1.84 gc is stabilized by a National NC1001 Atomichron frequency standard having a frequency stability of five parts in 10^{10} and a frequency accuracy of one part in 10^9 . The frequency synthesizer which enables the stabilization is described in paragraph 2.2.6. Performance characteristics of the AN/FRC-56(V) transmitting equipment are as follows:

Power Amplifier

Frequency Range	1.7 - 2.4 gc
Power output	10 kw
Power gain	40 db
Input	Type N connector, 50 ohms nominal, swr 1.2 maximum
Output	WR-430 waveguide flange
Primary power	208 v ac ± 5%
	60 ± 3 cps, 3-phase
	120 v ac ± 5%
	60 ± 3 cps, 1-phase
	4-wire

Bandwidth	± 500 kc at 0.5 db ± 3.5 mc at 3.0 db
Driving power	2 watts maximum

Exciter

RF frequency range	1.7 - 2.4 gc
RF power output	5 watts
External frequencies required	2 mc (+ 20 dbm) 50.0 mc (+ 13 dbm) 85-105 mc (+ 13 dbm)
Input impedance	50 ohms
Output impedance	50 ohms
Modulating frequency	250 cps to 70 kc
Modulation input impedance	150/600 ohms balanced/unbalanced
Test-tone peak deviation	140 kc in flat portion of preemphasis characteristic nominal ± 32 kc for -26 dbm input
Baseband pre-emphasis	12 μsec
Deviation capability	± 500 kc peak max.
Modulation frequency	± 1 db 500 cps to 8 kc ± 2 db 250 cps to 70 kc
Intermodulation distortion	-50 db max. using 50% random noise loading
Residual AM	-50 db max.
Residual FM	65 db below test tone level per 4 kc channel

2.2.4 Receiving Equipment

2.2.4.1 Configuration. The Floyd site receiving system employs low-noise, liquid-nitrogen-cooled parametric amplifiers. Dual diversity reception is provided with phase-lock tracking of doppler shifts. The parametric amplifiers and converter preamplifiers are located in an equipment house on the rear of the tracking antenna. Local oscillator energy is fed to the house at 1/4 or 1/6 the injection frequency via flexible coaxial line and received IF energy is returned to the equipment building below in the same manner. The dual-diversity doppler tracking receiver is located in the operations room and provides instrumentation outputs to measure signal intensity and doppler shift, as well as demodulating the received

signal. Receiver level calibration is accomplished by means of a crystal-controlled oscillator located in the operations room. The output of the calibration oscillator is taken via calibrated lines, pads, and directional couplers, to the inputs of the two receivers. Since the calibration lines to the two receiver inputs are adjusted for equal attenuation, the calibration system also can be used for diversity balance of the receiving system. The individual equipments which comprise the receiving system are described in the paragraphs which follow.

2.2.4.2 Parametric Amplifier. The parametric amplifier utilized is a dual-channel unit, an Airborne Instruments Laboratory Type 9321. A photograph of the parametric amplifier and cooling system installation (the Trinidad installation in this case), is shown in Figure 2-17. Two channels amplify, separately, the vertically and horizontally polarized components of the received signal. The amplifiers utilize Texas Instruments Type XD-502 Gallium Arsenide Varactors, which can be cooled to 78°K by means of an open-loop liquid nitrogen cooling system. K-band pump power is supplied by a common klystron oscillator for the Trinidad amplifiers and by two separate klystron oscillators for the Floyd amplifiers.

When operated with nitrogen cooling, the noise figure of the parametric amplifiers (including circulator losses and second stage contribution) is between 1.25 and 1.75 db, depending upon the characteristics of the individual varactor. The parametric amplifiers may also be operated uncooled, in which case the noise figure degrades to approximately 2.25 to 2.5 db. Loss between the receiver input and the antenna feed is approximately 0.75 db, resulting in a receiver temperature of approximately 200°K and a system temperature of approximately 240°K , with the parametric amplifier cooled.

The liquid nitrogen cooling system is constructed to permit operation at any antenna angle between horizon and zenith. One filling of liquid nitrogen (5 liters) is sufficient for somewhat over two hours of continuous operation.

The cooling system also permits approximately 24 hours of standby storage after filling before appreciable coolant evaporation occurs. A 5-liter transfer bottle is provided for charging the liquid nitrogen cooling system from the 110-liter bottle maintained in the operation building.

Significant characteristics of the parametric amplifiers are as follows:

Frequency range	1.7-2.4 gc (supplied fixed-tuned to 2.27 gc)
Power gain	17 db min.
Gain stability	± 0.2 db per hour ± 1.0 db per day
Noise figure	1.25 - 1.75 db
Allowable input swr	1.25 (referred to 50 ohms)
Output impedance	50 ohms
Phase stability	±5°
Bandwidth	25 mc typical
Spurious amplitude modulation	less than 1%
Overload point	-25 dbm for ± 0.5 db gain variation
Spurious responses	-60 db
Power supply	115 vac ± 5%, 60 cps ± 5%
Isolation between channels	60 db

2.2.4.3 Converter Preamplifier. The amplified signal from the parametric amplifier is converted to the 29.6-mc intermediate frequency in a dual channel converter amplifier also mounted in the receiving equipment shed on the rear of the tracking antenna. Alternate converter preamplifiers are available at the Floyd site; a dual-channel unit built by Microphase Corporation (Type R21724) and two modified converter panels from an AN FRC-56 receiver (Part CV-580/FRC-56) manufactured by Radio Engineering Laboratory. The converters contain multipliers for the local oscillator signal which is supplied from a frequency synthesizer in the 350-600 mc range. The local oscillator multiplication factor is 4 for the Microphase converter and 6 for the FRC-56

converters. Pertinent characteristics of the converter preamplifiers are as follows:

Frequency range	1.7 - 2.4 gc
Power gain	30 db (RF to IF)
Gain stability	± 0.1 db per hour ± 0.5 db per day
Noise figure	
AN/FRC-56 converters	8.0 db
Microphase converter	11.0 db
Permissible input swr	1.25 to 1 referred to 50 ohms.
Output impedance	50 ohms
Output frequency	29.6 mc
Local oscillator input frequency	
AN/FRC-56 converter	373.4 mc
Microphase converter	560.1 mc
Local oscillator input level	-10 dbm, 50 ohms
Bandwidth	4.5 mc
Spurious response	-60 db
Power supply	115 v ac ± 5%, 60 cps ± 5%
Interchannel isolation	30 db

2.2.4.4 Doppler Tracking Receiver

2.2.4.4.1 General. Doppler tracking and diversity combination is accomplished at the 29.6 mc IF frequency by means of a dual-diversity phase lock receiver.⁷ A photograph of this receiver is shown in Figure 2-18 and its block diagram is shown in Figure 2-19. This dual-channel receiver utilizes narrowband (100 cps) phase-lock loops to track and maintain synchronism with the doppler-shifted carrier of a received FM signal. Two military type R-390A/URR receivers are incorporated into the phase lock receiving system to provide IF gain and selectivity. Since the horizontal and vertical received signals are phase locked to a common reference oscillator, they are also maintained in phase with one another, permitting a predetection diversity combination. An equal-gain predetection combiner of this type is included in the receiver.

Conventional FM demodulation is provided with separate outputs for the horizontal, vertical and combined channels. In addition, the input frequency is regenerated from the phase-locked oscillator and supplied to an electron counter for accurate measurement of doppler shift. An AM detector to supply conical-scan tracking information and a signal-level monitoring output are also provided. The following specifications apply to the doppler-tracking receiver:

Type of circuit	dual diversity, phase lock for doppler-shift signals, FM demodulation for communications
IF input frequency	29.6 mc
Phase lock range	± 300 kc
Audio frequency response	300-3500 cps + 0-4 db
Type of tuning	Continuous electrical
De-emphasis	12 μ sec
Gain stability	± 0.5 db per hour ± 1.0 db per day
Phase lock monitoring	audio and oscilloscope Lissajous figure presentation
Audio power output	0 dbm (600 ohms)
Reconstructed carrier output	0.5 v rms (50 ohms)
Conical scan demodulated output	1 volt nominal at FM threshold 3 volts maximum
Interchannel isolation	60 db
Sensitivity	FM - 112 dbm at 29.6 mc for 20 db quieting CW phase lock 0 db s/n in 1 kc
Noise figure	10 db

2.2.4.4.2 General Scheme of Frequency Management. Figure 2-19 shows the operation of the system as a dual-diversity receiver: Although doppler shift on 29.5 mc is the major frequency shift which the VCO must degenerate, any drift in the crystal standard or in the permeability-tuned oscillator must also be degenerated. The latter drifts are removed in the doppler output by providing a mixer process complementary to the one in the receiver.

2.2.4.4.3 Description of System Components. The system is essentially modular. Apart from the power supply and two R-390A receivers, it consists of 10 chassis, each mounted on a panel 3-1/2 inches high, as follows:

2 each	Unit 1	Doppler Converter
2 each	Unit 2	Phase Detector
2 each	Unit 3	Voltage Controlled Oscillator
1 each	Unit 4	Metering Unit
2 each	Unit 5	Amplifier-Limiter
1 each	Unit 6	Combiner

2.2.4.4.4 Doppler Converter. The Doppler Converter is the double mixer, together with suitable buffers, used to remove the PTO and crystal reference frequency variations from the VCO frequency. The output is about 0.5 volts rms into a 50-ohm load and is intended to operate a frequency counter. Each input to the Doppler Converter is a nominal 50 ohms.

2.2.4.4.5 Phase Detector. The Phase Detector is of conventional design. Each input is brought in through a pentode buffer. The output floats and is eventually tied into the VCO ground. The unit has a nominal sensitivity (in the system) of 4 volts/radian. Each input impedance is about 1000 ohms.

2.2.4.4.6 Voltage Controlled Oscillator. The Voltage Controlled Oscillator is a push-pull double triode whose frequency is controlled by two capacitive diodes. After a buffer stage, it has two outputs with provisions for power division. One output develops about 1 volt into 50 ohms to drive the R-390A mixer whose input impedance is transformed to 50 ohms by an adapter mounted in or near the R-390A receiver. The other output, sent to the Doppler Converter, is provided by a circuit that contains an L network which transforms the 50-ohm load to about 2000 ohms before bridging it across the low-impedance VCO output.

The dc bias voltage which sets the quiescent frequency of the VCO is developed across a 10-turn potentiometer (front panel control) and metered at the VCO. The output of the Phase Detector, which is connected in series with the dc bias and also metered at the VCO, is applied as a control voltage to the VCO through a conventional, proportional-plus-integral filter consisting of two 22-megohm resistors, a 10K-ohm potentiometer (on rear panel) to control the damping factor, and a 40-microfarad condenser. A filter bypass pushbutton provided as a front panel control prevents the long time-constant of this filter from interfering with attempts to adjust the quiescent frequency.

The VCO has a nominal sensitivity (in the system) of 1 mc/volt.

2.2.4.4.7 Metering Unit. The Metering Unit contains a 455-kc crystal reference oscillator and a 1-inch oscilloscope tube with switching such that channel H (horizontal) IF can be viewed versus reference oscillator; or channel V (vertical) IF versus reference; or channel H versus channel V when both have been locked. Also contained in this unit are a VU meter and a carrier-level meter which are separately switchable to indicate the output audio level of the H or V or C (combined) channels or the carrier level in any channel just after the last linear amplifier. This unit is transistorized.

2.2.4.4.8 Amplifier-Limiter. The Amplifier-Limiter has a low-impedance input followed by two stages of linear gain, at which point the unit provides a low-impedance output to the Combiner. Also at this point, a high-impedance diode detector supplies an output for a carrier-level indicator and/or a conical-scan detected output, in case the receiving antenna is scan controlled. Two subsequent stages of limiting provide a low-impedance output to feed the Phase Detector and, at a higher impedance level, a signal for a Weiss frequency discriminator within the Amplifier-Limiter. After frequency discrimination, the signal is fed to an audio amplifier with transformer-coupled, adjustable output supplying nominally 0 dbm to 600 ohm.

2.2.4.4.9 Combiner. The Combiner is a simple adder. The input stage consists of two cathode followers whose outputs are added. A switch is provided so that either horizontal or vertical IF signals or both can be applied as inputs. After the input stage, the unit is essentially the same as the Amplifier-Limiter, except that one stage of linear gain is omitted.

2.2.5 Tracking

2.2.5.1 General. The half-power beamwidth of the Floyd 33-foot tracking antenna at 2 gc is approximately 1.0 degree. The required tracking accuracy is 0.1 degree, or about 1/5 the half-beamwidth. An rms tracking error of 0.1 degree will result in an rms degradation in signal level of approximately 0.25 db and the introduction of less than 0.5 db peak-to-peak fading.

Three tracking modes have been provided at the Floyd facility. The two radio modes involve passive tracking on either the 425-mc radar frequency or the 2270-gc received communications frequency. The radar mode utilizes a monopulse feed consisting of four cavity spiral antennas arranged about the dual-polarization communications frequency feedhorn. The communications frequency tracking also utilizes a monopulse feed, but to simplify the tracking system with respect to receiver and duplexing filter requirements, a conically scanned beam is artificially generated from the monopulse output. This feed system was described in Paragraph 2.2.2.

The optical tracking mode permits the antenna to track visible satellites under operator control. Although intended primarily as an acquisition aid, the optical tracking system is capable of sufficient accuracy to permit continuous communication at night during unobscured visible-satellite passes. A selector switch in the control room permits selection of either of the automatic radio tracking modes, optical tracking, or manual antenna control.

2.2.5.2 Radar-Frequency Tracking. The radar frequency tracking equipment is the system that was used in the initial Echo I experiments² and it has been little modified under the present contract. A discussion of the radar frequency tracking system is included here, however, for the sake of completeness.

A monopulse antenna configuration is used consisting of four cavity spiral antennas spaced about the 2-gc communications feed at the focus of the 33-foot Floyd tracking antenna. Stripline hybrids also located at the focus of the antenna resolve the spiral outputs into sum, elevation difference, and azimuth difference signals. In the radar tracking receiver, the elevation and azimuth error signals are used to control the amplitudes of 10 and 15-kc side-bands so that a common IF amplifier can be used for the composite df signal. The IF bandwidth used is 50 kc to permit all sidebands of the composite df signal to pass and leave sufficient space on either side to accommodate the maximum doppler shift anticipated. After a baseband detection, the subcarriers corresponding to the individual error voltages are filtered in narrower filters and detected.

The threshold sensitivity of the 425-mc monopulse tracking system at Floyd is approximately -127 dbm. Although this sensitivity was apparently marginally adequate for tracking the Echo I satellite at the time of launch, the reflected signal now obtained falls below this threshold. The reflected signal anticipated from the rigidized 135-foot Echo II satellite, however, should provide satisfactory tracking for all mutually visible satellite positions. A relatively simple modification to substantially improve the radar tracking system threshold and permit operation with the degraded Echo I satellite or other objects of smaller cross section is suggested in Section 7 of this report.

2.2.5.3 Communication-Frequency Tracking. A more accurate system for radio tracking of passive satellites is provided by the communications frequency tracking system at Floyd. This system passively tracks on the received 2.27-gc communication signal transmitted from Trinidad and reflected by the satellite. An artificial conical scan feed (described in Paragraph 2.2.2) utilizes a four-horn illuminating aperture. The artificial conical scanning is introduced on both the vertically and horizontally polarized received signals. The crossover level is adjustable from 0 to 10 db with a nominal value of 0.5 db being utilized for tracking operations.

Two quadrature-phased reference signals at the scan rate are generated by rotating a 400-cps resolver in synchronism with the rotary phase shifter which generates the conical scan. The scan frequency envelope is subsequently recovered from the 400-cps carrier in a synchronous detector.

The amplitude modulation impressed upon the received signal by the scanning of the antenna beam is recovered in an envelope detector in the doppler-tracking communications frequency receiver. Synchronous detection of this AM envelope against the appropriate scan-frequency reference signal yields the elevation or azimuth error signal, which is filtered and applied to the servo system. Apart from the filtering provided in the conical scan demodulator, the servo-loop constants of the original installation are preserved.

2.2.5.4 Optical Tracking. A U.S. Navy Mk 51 gun director is the basic element of the optical tracker installation at the Floyd site. The steering mechanism and servo system of the 33-foot reflector at the site consists of a modified U.S. Navy Mk 32, Mod 4, twin 5-inch gun mount. The Mk 32 mount and the Mk 51 director were designed to work together in their original ship-board applications; thus only minor modifications to the Mk 51 director were required to convert it to a suitable optical tracker.

The optical tracker is mounted on a 10 x 10 x 1-foot reinforced concrete pad near the center of the Floyd Test Site area, 700 feet north-northwest of the 33-foot antenna tower.

At the time of installation this location provided the most favorable field of view for tracking satellites mutually visible to both the Floyd and Trinidad sites. Since installation, work has begun on a 60-foot tracking antenna 300 feet east of the optical tracker. This tower will obstruct the field of view of the optical tracker for angles below 15° in an easterly direction.

Modification to the Mk 51 director consisted of the addition of a telescope mounting assembly bolted to the top of the director in a position so that sighting through the telescopes is convenient for the operator. Two telescopes, one for acquisition and one for tracking, are clamped to the

mounting assembly. Fine adjustment screws permit accurate alignment of the telescopes. The construction of the telescope clamps is such as to permit easy removal and replacement of the telescopes without disturbing alignment adjustments.

The acquisition telescope is a Bausch and Lomb Balscope Sr. type providing a 2.7° field of view and 15x magnification. A Bausch and Lomb Balvar 24 telescope is used for tracking. Magnification of the tracking scope is adjustable between 6x and 24 x to suit the convenience of the operator.

The optical tracker is connected to the site equipment building by 850 feet of 11-pair buried cable which provides for data circuits and one sound-powered telephone circuit.

The optical tracker is required to permit an operator to follow visible satellite to an accuracy of 0.2 degree. An early measurement indicated that an untrained operator can attain this accuracy even in uncomfortably cold weather. With training, and under favorable conditions, it is believed that operator error can be held well below 0.1 degree. Error analysis with respect to the 2-gc pattern of the Floyd antenna indicates that a 0.2-degree rms optical pointing error combined with a 0.1-degree rms tracking error will produce a signal degradation of approximately 0.7 db and introduce about 2 db peak-to-peak fading. This indicates the practicality of utilizing the optical tracker for primary tracking during visible passes.

2.2.6 Frequency Control

Both the transmitters and receivers at the Floyd site are frequency controlled by a National NC-1001 Atomichron frequency standard. The

Atomichron is a cesium-resonance primary frequency standard having the following characteristics:

Output frequencies	100 kc, 1, 5, 10, and 100 mc
Frequency stability	5×10^{-10}
Frequency accuracy	10^{-9}

In the receiving equipment, the local oscillator injection frequency of 2240.4 mc is stabilized by means of a Schomandl Type FD-3 frequency synthesizer which generates a frequency of either 560.1 or 373.4 mc from the 100-kc and 5-mc outputs of the Atomichron. Frequency synthesis in the Schomandl unit is accomplished by means of two phase-locked loops which operate on harmonics of 10 mc and 100 kc.

Originally, the Schomandl synthesizer utilized only the 100-kc output of the Atomichron, which was effectively multiplied by a factor of 5601. Measurements, however, showed that substantial spurious deviation existed on the 100-kc output of the Atomichron, resulting from the type of frequency synthesizer used. Discussions with the National Company confirmed the existence of these spurious deviations even in a properly adjusted Atomichron. This, coupled with the large multiplication ratio, resulted in excessive FM noise on the receiver local oscillator injection. Since the 5-mc output of the Atomichron was relatively free of this spurious deviation, a modification was made to the Schomandl frequency synthesizer whereby the 10-mc frequency multiplier chain was broken at the 5-mc point, and the 5-mc output of the Atomichron introduced at this point. This modification reduced the contribution of the 100-kc spurious deviation by a ratio of 5600/1.

The output of the Schomandl frequency synthesizer is fed to the antenna rf house through a length of RG-9B/U coaxial cable. Further multiplication to the injection frequency is accomplished in the converter

preamplifier. The Microphase preamplifier multiplies a synthesizer output of 560.1 mc by 4, while the AN/FRC-56 converter unit multiplies a synthesizer output of 373.4 mc by 6 to obtain the 2240.4-mc local oscillator signal. The receiver IF frequency (29.6 mc \pm doppler) is returned to the building through coaxial cable. In the phase-lock doppler tracking receiver (described in Paragraph 2.2.4.4), the additional translation frequencies (2.6 mc and 455 kc) are subtracted from the frequency of the phase-locked oscillator to regenerate the received IF frequency, which is counted on an electronic counter to provide a measure of Doppler shift. Operation of the doppler conversion portion of the receiver is described in the receiver manual⁷.

As described in Paragraph 2.2.3 of this report, the Floyd transmitter frequency is derived from frequencies of 2, 50, and 89.1111 mc. These frequencies are in turn derived from the 1 mc, 10 mc, and 100 mc outputs of the Atomichron frequency standard by means of the Page Type F synthesizer shown in block diagram form in Figure 2-20. This synthesizer utilizes regenerative frequency dividers for frequency conversion, as described in its instruction manual.⁸

2.2.7 Instrumentation

2.2.7.1 Data Collection. Four basic modes of data collection are used at the Floyd facility. These modes are magnetic tape recording, strip chart recording, digital electronic counter printout, and photographic antenna orientation recording.

Two dual-channel Ampex Type 960 magnetic tape recorders comprise the magnetic tape recording facility. The recorders provide four 7.5-kc channels which normally are allocated as follows:

Channel A	Operator's intercom
Channel B	Communications receiver baseband output, combined channel

Channel C	Communications receiver baseband output, vertical channel
Channel D	Communications receiver baseband output, horizontal channel

Time reference is provided by periodic time checks by one of the operating personnel on the intercom channel.

Two Brush Type RD-1684-00 strip chart recorders provide 16 analog and 4 event-type strip chart recording channels. These channels normally are allocated as follows:

Recorder No. 1

Channel 1	Radar-frequency df carrier level
Channel 2	Horizontal communications carrier level
Channel 3	Vertical communications carrier level
Channel 4	Combined communications carrier level
Channel 5	Azimuth tracking error
Channel 6	Elevation tracking error
Channel 7	Azimuth tracking rate
Channel 8	Elevation tracking rate
Event Marker 1	Atomichron time ticks
Event Marker 2	Controller's reference marks

Recorder No. 2

Channel 1	Azimuth fine position
Channel 2	Elevation fine position

Channel 3	Azimuth coarse position
Channel 4	Elevation coarse position
Channel 5	Beacon signal level
Channel 6	Not allocated
Channel 7	Not allocated
Channel 8	Not allocated
Event Marker 1	Atomichron time ticks
Event Marker 2	Controller's reference marks

As explained in the preceding section, the received IF frequency of the communications receiver is regenerated by appropriate translation of the phase-lock oscillator frequency. Since the local oscillator injection frequency is Atomichron controlled, doppler shift of the received signal is directly translated to the IF frequency. The regenerated IF frequency (29.6 mc + doppler) is counted by a Hewlett-Packard Type 524 Electronic Counter. A once-per-second digital readout provides an accurate record of the doppler shift associated with the received communications signal.

Time sequential photographic records of the beam alignment of the Floyd tracking antenna are provided during optically visible satellite passes. For this purpose a Robot semi-automatic camera is used with a one-second frame rate determined by an external timer. Exposure per frame for satellites of the Echo I or Echo II type is 1/4 second with Tri-X film. A 650-millimeter, f/5.5 lens is used.

The boresight camera is enclosed in a weatherproof housing with snap fasteners to permit access for changing of film. Incorporated in the Rotot automatic camera is a secondary image prism, which provides a reference presentation in one corner of each picture frame. Included in the

field of the secondary image are antenna elevation and azimuth readouts, a frame counter, and a series of indicator lights to designate the tracking mode in use. A photograph of the boresight camera (as installed at Trinidad) is shown in Figure 2-21.

2.2.7.2 Test Equipment. The following items of test equipment are provided at the Floyd Site:

1. Adjustable Line, General Radio Type 874-LA
2. Adjustable Stub, General Radio Type 874-D20
3. Adjustable Stub, General Radio Type 874-D50
4. Amplifier, Unit IF, General Radio Type 1216-A
5. Attenuator, Adjustable, General Radio Type 874-GA
6. Attenuator, ARRA, Model No. 1414-10A (three)
7. Attenuator, ARRA, Vamp Model No. 1414-10
(2 available)
8. Attenuator, 20-db, Microlab AF-20
9. Attenuator, VHF, Hewlett Packard Model 355A
10. Crystal Mixer, General Radio, Type 874-MR
11. Crystal Oscillator, Philco 2270 Mc sec
12. Detector, Crystal, Hewlett-Packard 420A
13. Detector, Crystal, Hewlett-Packard X421A (two)
14. Directional Coupler, Dual, Hewlett Packard Model 7670
15. Directional Coupler, 12.25-db Melabs X144
16. Frequency Counter, Hewlett-Packard 524D with 525A and
525B Converters, (available as test equipment, but
actually part of doppler readout system)
17. Filter, High Pass, Microlab FH-1501
18. Generator, UHF, TS 403/U
19. Generator, VHF, Hewlett-Packard 608C (two)
20. Generator, VHF, Hewlett-Packard 608D

21. Meter, Carrier Deviation, Marconi TF 791D
22. Meter, Microwave Power, Sperry Model 123B
23. Meter, Noise Figure, Hewlett-Packard 340B
24. Mount, Barretter, Sperry Model 33B3
25. Mount, Detector, Hewlett-Packard 440A
26. Noise Generator, Hot-Cold Body, Type 70, AIL
27. Noise Source, Argon, AIL Model 7010
28. Oscilloscope Preamplifier, Tektronix, Type CA
29. Oscilloscope, Tektronix 512
30. Oscilloscope, Tektronix 515A
31. Oscilloscope, Tektronix 533
32. Oscilloscope, Tektronix RM 16
33. Oscillator, Test, Hewlett-Packard 200CD
34. Oscillator, Test, Hewlett-Packard 650A
35. Oscillator, Transfer, Hewlett-Packard 540B
36. Oscillator, Unit, General Radio Type 1209BL
37. Recorder, Digital, Hewlett-Packard 560A
38. Slotted Line, General Radio Type 874-LBA
39. Synthesizer, Schomandl, Type FD3
40. Tube Tester, Hickok 1575
41. Unit Power Supply, General Radio 1201B
42. Voltmeter, Simpson Model 270 (two)
43. Voltmeter, Vacuum Tube, Hewlett-Packard Type 400D
44. Voltmeter, Vacuum Tube, Hewlett-Packard Type 410B

2.2.8 Primary Power.

The primary power substation feeding the Floyd Site experimental space communications facility required expansion to provide the additional power required for the 2-gc exciter and 10-kw power amplifier. This

expansion was accomplished by the addition of three 50-kva transformers to the existing substation. The present capacity of the station is:

75 kva	440 volts	3 phase
15 kva	110 volts	1 phase
150 kva	208 volts	3 phase

The existing local distribution lines were terminated in a switch panel in the base of the concrete antenna tower. This was left unchanged. The added local distribution lines were terminated in two switch panels installed in the equipment building near the antenna tower.

Two concrete manholes were constructed to contain the junctions of the incoming 4160-volt, 3-phase line with the feeder lines to the primary of each of two transformer bays.

The existing concrete pad was extended to provide mounting space for the three added 50-kva transformers. The existing 6-foot chain link fence was enlarged to contain the enlarged concrete pad.

2.3 TRINIDAD FACILITY

2.3.1 Site Description

The Trinidad terminal of the experimental passive satellite communications facility is located at the Atlantic Missile Range radar tracking site on the U. S. Naval Station, Chaguaramas, Trinidad. The communication system shares an 84-foot diameter parabolic tracking antenna with the AN/FPT-5 radar. The equipment building is located beneath the antenna pedestal as shown in the site plot plan, Figure 2-22.

The equipment configuration at Trinidad is in many respects similar to that at Floyd. The major difference is in the tracking, which is provided at Trinidad by the AN/FPT-5 radar illuminating the 84-foot antenna simultaneously with the communication signal. The feed arrangement for simultaneous operation is described in Paragraph 2.3.2.

A block diagram of the Trinidad system is shown in Figure 2-23. Major items of equipment are listed in Appendix B. The individual subsystems and equipments are described in the paragraphs which follow.

2.3.2 Antennas and Transmission System

2.3.2.1 Requirements. In the use of satellites for communication, it is essential that the transmitting and receiving antennas be directed toward the satellite. Especially with the high path loss of a passive system, where high-gain antennas are required, precise tracking data is a necessity. For the communications capability then, it is necessary to provide a high gain antenna slaved to a tracking radar or to provide a dual tracking and communication capability in a common beam-forming aperture. From the cost standpoint the latter approach has an overwhelming advantage and it is the method chosen here.

With a satisfactory radar tracking system already existing in Trinidad, the requirement was to add the communications frequency capability to the radar antenna with an absolute minimum of degradation to the radar function. The radar considerations which limit the approaches to the problem are antenna mismatch, power loss, beam distortions which affect tracking accuracy, and ability to maintain the present radar capability of operating in either vertical or horizontal linear polarization or either left or right hand circular polarization. These must be achieved with the communications feed system in place in order to achieve the very desirable capability

of not having to add feeds and change radar polarization modes for communications operations.

Since the existing radar feed covers a large area about the antenna focal point and cannot practically be modified or moved, there is no possibility of other feed sources in the focal area to achieve proper illumination. This difficulty suggests a form of Cassegrain system, which by its nature permits the focusing of rays to a point other than the primary focal point of the collimating reflector. The classical Cassegrain geometry employs a parabolic contour for the main dish and a hyperbolic contour for the subreflector. One of the two foci of the hyperbola is the real focal point of the system, and is located at the center of the feed in a region between the subreflector and main reflector; the other is the virtual focal point which is located at the focus of the parabola. By fabricating a structure that will efficiently transmit the energy from the source at the focal point of the parabola, and also efficiently reflect the energy from a source located at the real focal point of the Cassegrain system, the resultant effect will be to collimate both beams along the axis of the parabola.

There are a number of forms of the Cassegrain system covered by Hannan⁹ some of which perform functions of this problem but in a more limited scope. None of the systems described permits simultaneous full use of the paraboloid aperture without the disadvantage of polarization sensitivity. As previously stated, this system must permit the radar to function with either vertical or horizontal linear polarization or circular polarization of either sense. In addition, the two communications frequencies must be capable of receiving orthogonal linear polarizations simultaneously.

2.3.2.2 Feed Geometry. The basic geometry of the Trinidad system is shown in Figure 2-24. Figure 2-25 illustrates the concept of the frequency-selective reflector with the lower frequency radar energy shown passing through

the "space filter" and the higher frequency communications energy reflected back to illuminate the parabolic reflector.

Having in theory a system that will permit simultaneous illumination of the paraboloid, it must be established that a radome-reflector to perform the subreflector function is feasible.

The most obvious first approach to a solution of the reflector problem is the use of solid homogeneous dielectrics. Anyone having worked on or familiar with efforts to construct broadband radomes is fully aware of the narrow passband characteristics of the dielectric sheet. The broad frequency separation here, a radar frequency of 425 mc and communications frequencies of 1840 and 2270 mc, indicates that the natural solution is to construct a structure with thin-wall pass characteristics at the lower frequency and high-rejection properties at the two communications frequencies.

When radiation is normally incident on a plane sheet of dielectric material, part of it is reflected at the front surface; the remainder enters the sheet and is partially reflected at the back surface. Some of this wave that is reflected at the back surface re-emerges at the front surface and is directly superimposed on the originally reflected portion; part of it undergoes multiple reflection in the sheet and further contributes to the resultant reflection. In general, the resultant reflection from the back wall would be expected to be equal in magnitude but opposite in phase to that from the front wall, and thus would cancel it. If this were not so, there would be a sudden discontinuous jump from no reflection for no sheet to an appreciable one of finite value for an infinitesimally thin sheet. Such discontinuities are rarely found. The expectations are confirmed by the electromagnetic theory of the reflection: the amplitude-reflection coefficients for the two surfaces are equal in magnitude but opposite in sign, and the amplitude of the resultant reflected wave approaches zero for a sheet of infinitesimal thickness.

When the thickness of the sheet of dielectric material equals one-quarter wavelength in the material, the wave reflected from the back surface will have traveled one-half wavelength more than the wave reflected from the front surface and will be in phase with it. For this thickness the reflection should again be a maximum.

Since the magnitude of the reflection is limited by the index of refraction of the material, it is required that a dielectric with a relatively high dielectric constant be used. The curves of Figures 2-26 and 2-27 were based on formulas from Cady et. al.¹⁰, for relative dielectric constants of 9 and 25. The figures present plots of the power reflection coefficients, and by selecting a suitable thickness the efficiency at the three frequencies can be readily obtained. The curves represent the idealized case of normal incidence and lossless medium. It can readily be seen that for the frequency assignment given, this approach falls short of being able to meet the desired characteristics of 98% transmission at 425 mc., and 50% minimum reflected power at 1840 and 2270.mc.

2.3.2.3 Artificial Dielectric Reflector. In view of the inability of conventional materials of high dielectric constant to fulfill the requirements, the use of artificial dielectric means was investigated. It is known^{11, 12} that the action of solid dielectric can be reproduced by making a large scale model of a molecular structure. Since conductors become polarized under the action of an electric field, they can be used to replace the molecules of the dielectric, and the model becomes a lattice of conducting elements.

Under normal applications there are two requirements which are imposed on the lattice structure. First, the spacing of the elements must be somewhat less than one wavelength of the shortest wavelength to be transmitted, otherwise diffraction effects will occur. Secondly, the size of the elements must be small relative to the minimum wavelength so that

the resonance effects can be avoided. The first resonance occurs when the element size is approximately one-half wavelength, and for frequencies in the vicinity of this resonant frequency, the polarization of the element is not independent of frequency.

Another way of looking at the wave delay produced by lattices of small conductors is to consider them as capacitive elements which load free space, just as parallel capacitors on a transmission line act as loading elements to reduce wave velocity. The derivation and experimental evaluation of equivalent shunt susceptances of planar arrays of conducting discs was given in a report by Gardner.¹³ The details of such an array are shown in Figure 2-28(a) and the equivalent circuit for the structure is shown in Figure 2-28(b). Thus the problem of designing an artificial array of discs is relegated to a transmission line solution.

Although in the normal artificial dielectric, the disc diameters are made small so that the effective index of refraction will be near constant with frequency, in the present case a nonconstant characteristic is desired of the medium. More specifically, it would be desirable to have a high index of refraction at 1840 and 2270., and a low index at 425 megacycles. This requirement may be directly translated to a high capacitive susceptance at the higher frequencies and low capacitive susceptance at 425 mc. Kock¹¹ states that when the elements approach a half-wavelength in their length parallel to the electric vector, resonance effects occur, and the index of refraction of the artificial dielectric will increase rapidly. That is, as the element approaches $\lambda/2$, the dielectric will appear opaque.

These known characteristics were the basis for design of the frequency-selective subreflector which permits simultaneous collimation of the radar and communications beams. The approach in this case was to fabricate a structure madeup of rings of aluminum which approached the

resonance region at the higher frequencies. These rings present a very high susceptance at communications frequencies. However, since their diameter at 425 mc is still a small fraction of a wavelength, the behavior at this frequency is as a dielectric material with a low refractive index. A second sheet of smaller rings of a closer spacing was used to produce an equal susceptance at the radar frequency, and being well removed from the resonance region at the communications frequency, its effect was small in comparison to the first sheet.

These two sheets were combined, using transmission line matching principles, in a manner to produce essentially zero reactive loss at 425 mc and appear as a single highly reactive sheet at the higher frequencies. The filter structure thus provides frequency discrimination by selective reflection, permitting simultaneous illumination of the 84-foot reflector by the radar feed located at the primary focus and the communications feed located at the secondary focus.

2.3.2.4 Feed Construction. Figure 2-29 illustrates the basic form of the reflector-radome as constructed. The unit in operation at Trinidad was developed empirically, since no data was available on the behavior of the ring elements and their spacing effects in the region approaching resonance.

The reflector was initially constructed with the rings laid on the opposite sides of a six-foot diameter styrofoam block approximately seven inches thick to provide the proper spacing between ring arrays. The entire structure was then covered with fiberglass and resin, tying the mounting brackets in and providing weatherproof construction. Although the foam material was the lowest in loss of any obtainable, it also had very good thermal insulation properties and could not dissipate the rf heat rapidly enough. Since the foam could not withstand the high radar energy concentration in the center, redesign was necessary. The final configuration retained

the same construction in the outer foot of radius to provide a rigid structure. The foam was removed from the center section of four-foot diameter, leaving the center hollow with the rings sandwiched between thin sheets of silicone fiberglass and secured to the two faces of the reflector radome. The tuned reflector provides 98% transmission at 425 mc and approximately 80% reflection at 1840 and 2270 mc.

The dielectric structure is secured in place by eight fiberglass tubes tied to a mounting ring clamped to the outer structure of the 425-mc feed. Coarse and fine positioning adjustments are attained by positioning the clamp on the radar feed housing and by mounting bolt adjustments provided in securing the mounting ring to the clamp. The communications feed horn is tied in place with respect to the subreflector and the radar feed, by four fiberglass tubes between the feed horn and the mounting feet on the sub-reflector. This assures that any deflection of the radar feed causing a beam shift of the radar beam will result in a corresponding shift of the communications beam and a common axis will be maintained. A photograph of the Trinidad antenna feed is shown in Figure 2-30.

The dual-polarized feedhorn is fed through orthogonal arms by two waveguide runs which are secured to the radar feed stack. The radiating aperture is 4 inches square in a 6-inch diameter ground plane. The horn is pressurized by a thin sheet of silicone fiberglass sealed across the aperture. The Trinidad feed and transmission system are shown diagrammatically in Figure 2-31.

2.3.2.5 Duplexer. The duplexer, or branching filter, permits simultaneous transmission and reception on separate frequencies without interference through a common feed line to an antenna. The duplexer, which is identical to the unit installed at Floyd, is made up of a transmit frequency bandpass filter, a receive frequency bandpass filter, and a common junction between

them feeding to the antenna. The filters are constructed of WR-430 waveguide with inductive irises and capacitive tuning screws forming in-line resonant cavities, four of which are used in each filter arm. With the proper spacing of irises and by tuning the filters, the selected frequency is passed through with a minimum of loss, while the filter appears highly reactive to reject out-of-band signals.

The receive filter is of the same direct-coupled cavity construction as the duplexer filter arms. This unit is in the receive line feeding the arm of the feed horn, which is orthogonal to the duplexed arm input. It serves the same function as the receive arm of the duplexer, to reject the transmitted energy, which could interfere with the reception of the desired signals. The duplexer is mounted on the back of the parabolic reflector and moves with it. In this way any noise generated in the rotary joints which is in the passband of the receive filters will be rejected by the transmit arm of the duplexer. In addition the parametric amplifiers are mounted on the back of the paraboloid, keeping the receive transmission lines as short as possible and eliminating the need for additional rotary joints. As at the Floyd site, directional couplers in the receive arms of the waveguide runs are provided for the purpose of feeding calibration signals to the inputs of the parametric amplifiers.

2.3.2.6 Transmission System. The capability for operating over the angular range of the antenna in elevation is provided by a rotary joint in the elevation axis. Coverage of 360° in azimuth is achieved by a 45-foot coil of flexible waveguide riding on rollers around the azimuth axis. The flexible waveguide is connected only during communications operations, and during these operations limit switches in the antenna drive circuits preclude damaging the flexible section by exceeding its physical capabilities. The azimuth waveguide wrap-up assembly is shown in Figure 2-32. The remainder of the

waveguide runs are of standard WR-430 aluminum construction with short pieces of WR-430 flexible guide as required.

2.3.2.7 Performance. Significant performance parameters of the Trinidad antenna and transmission system are as follows:

Antenna gain	52.0 db
Antenna H-Plane beamwidth	26'
Antenna E-plane beamwidth	27'
Transmission system loss, feed to horizontal receiver input	0.7 db
Transmission system loss, feed to vertical receiver input	0.7 db
Transmission system loss, transmitter to feed	2.3 db
Antenna temperature including feedline and filter losses (above 8° elevation)	120° K
Subreflector transmissivity 425 mc	0.98
Subreflector reflectivity 1340 mc	0.8
Subreflector reflectivity 2270 mc	0.8

2.3.3 Transmitting Equipment

2.3.3.1 General. The Trinidad site is equipped with an AN/FRC-56 exciter and power amplifier, delivering a power output of 10 kw at 2270 mc. This transmitter was installed as part of the simplex communications link under Air Force contract AF 30(602)-2016. Several modifications have been made to the exciter and power amplifier under the present contract:

- (a) The exciter has been modified to permit external frequency control by an Atomichron primary frequency standard.
- (b) The power amplifier has been equipped with a beam pulser to permit operation of the Trinidad terminal in a 2270-mc radar mode.
- (c) Exciter noise and distortion at low modulation frequencies has been reduced to permit satisfactory operation at low deviation ratios.

2.3.3.2 Exciter Modification for External Frequency Control. The AN/FRC-56 exciter is normally crystal controlled, the output frequency determined by three crystal oscillators. Originally, the modulator operated at 1.5 mc, was multiplied to 4.5 mc, then mixed to 38.0 mc by injecting a 42.5 mc signal. The 38 mc fixed-frequency signal was then mixed with a third crystal oscillator signal at 101.06 mc. and multiplied by 36 to produce the 2270-mc operating frequency. After modification, the modulator operated at 2.0 mc, was multiplied to 12 mc, mixed to 38 mc by injecting a 50-mc signal, mixed to 63.055 mc by injecting 101.0555 mc, and then multiplied to 2270 mc as before. This change permitted the use of a simple frequency synthesizer which produces the 2, 50, and

101.0555-mc injection signals from the Atomichron primary frequency standard. Modifications of the exciter to provide input terminals and to change the tuning range of several stages are described in a modification manual.¹⁴ The synthesizer, which derives 2, 50, and 101.0555-mc signals from the Atomichron frequency standard, is described in its manual.¹⁵

2.3.3.3 Klystron Beam Pulser. In order that klystron noise output not obscure the received signal between output pulses in the radar operation mode, a hard-tube beam voltage pulser was installed in the AN/FRC-56 power amplifier. The pulser was built by Amicon Corporation to specification PCE-S-8541A, and is described in the referenced specification and in the instruction manual¹⁶. Briefly, the pulser consists of a high vacuum beam tetrode, Eimac 4PR1000A, which is switched into a series connection with the negative high-voltage lead to the klystron power amplifier. In the pulsed mode of transmitter operation, the tube is keyed from an external Rutherford model B7 pulse generator to produce pulses of about 16 kv across the VA-800 klystron amplifier tube. The pulser assembly is mounted on the side wall inside the FRC-56 control cubicle.

The pulser is capable of keying the transmitter with pulses from 10- μ sec to 3-msec width, at repetition frequencies from 20 cps to 500 cps. Klystron excitation is keyed in synchronism with the beam voltage, resulting in rf envelope rise and fall times of the order of 0.25 μ sec. Noise between pulses is reduced to a value considerably below the receiver noise level.

2.3.3.4 Exciter Noise and Distortion Reduction. In view of the low modulation index used on the system and the low modulating frequencies, it was necessary to give considerable attention to the reduction of hum

modulation in the exciter. It was found in particular that the ground returns in the audio portion of the exciter were poorly made, using the tube socket mounting strap-nuts. Providing star washers under the strap nuts alleviated this source of hum. Additional filter capacity was connected across the audio section plate supply and the audio grounds were modified to remove ground loops. Additional hum reduction may be obtained if necessary by removing the input audio amplifier, V3007, and connecting the audio attenuator to V3008. The additional gain of V3007 is not required for normal operation of this installation. Exciter audio distortion noted during operation under the previous contract, was found to be caused by a wiring error in the serrasoid modulator, which has now been corrected.

2.3.4 Receiving Equipment

Except for the operating frequency, the means by which the injection frequency is derived and the parametric amplifier difference described in paragraph 2.2.4.2, the Trinidad receiving equipment is identical to that used at the Floyd site, described in Paragraph 2.2.4. The injection frequency used is 1810.56 mc, which results in an IF center frequency of 29.44 mc. The frequency synthesizer is discussed in Paragraph 2.3.6. An AIL dual-channel parametric amplifier, Microphase Corp. converter-preamplifier, and Page dual-diversity phase-lock receiver identical to that used at the Floyd site, are utilized. These units are tuned to the Floyd transmitting frequency of 1840 mc.

2.3.5 Tracking

Tracking at the Trinidad terminal is accomplished by the AN/FPT-5 radar facility, either in the active radar mode, or with an orbital programmer controlled by punched paper tape. The normal active mode has been used for tracking the Echo I satellite, and the orbital programmer for moon-bounce tests. Active tracking of the moon is not feasible, since the antenna will nutate around the periphery of the moon due to the conical scanning system. This effect substantially reduces the illumination of

useful reflecting area by the communications transmitter. Optical measurements of the active tracking accuracy on the Echo I satellite indicate a tracking precision adequate for the communications experiments.¹⁷

2.3.6 Frequency Control

Both the transmitting and receiving systems at Trinidad derive their frequency control from the Atomichron primary frequency standard. The Trinidad frequency control system differs in several respects from that used at Floyd. Exciter injection frequencies of 2, 50, and 101.0555 mc are obtained from the Page Type T frequency synthesizer, which operates from the 1, 10, and 100 mc Atomichron output signals. Figure 2-33 is a block diagram of the Type T frequency synthesizer, described in detail in the instruction manual.¹⁵ As described in Paragraph 2.3.3, the Trinidad AN FRC-56 exciter was modified to permit external frequency control. Residual FM has been reduced to a deviation of 300 cps, principally noise.

The receiver injection frequency of 1810.56 mc is derived by multiplying by four in the varactor multiplier in the converter-preamplifier unit and by forty in the Schomandl NB-7 harmonic amplifier, from a synthesized 11.316-mc signal. The Schomandl ND-5 frequency synthesizer has been modified to use both the 5 mc and 100 kc Atomichron outputs, as at the Floyd site. This has resulted in lowering the residual frequency deviation at the injection frequency to 30 cps. In order to compensate losses in the long transmission line from the synthesizer to the converter, an Applied Research Inc., Model UH-2(a) amplifier has been installed following the NB-7 harmonic amplifier.

2.3.7 Instrumentation

2.3.7.1 Data Collection. The four basic modes of data collection employed at Trinidad are identical to those utilized at Floyd and consist of

magnetic tape recording, strip chart recording, digital electronic counter printout, and photographic antenna-orientation recording.

Two dual-channel Ampex type 960 magnetic tape recorders providing four 7.5-kc recording channels are provided at the Trinidad site. During operation one of these recorders is normally employed in the playback mode to provide baseband modulation for the transmitter. The second recorder provides recording channels for the communications receiver baseband output (combined channel) and operator's commentary.

Eight analog and one event-type strip-chart recording channels are provided by a Brush Type RD-1664 strip chart recorder. These channels are normally allocated as follows:

Channel 1	Doppler shift (from counter analog output)
Channel 2	Antenna azimuth
Channel 3	Antenna elevation
Channel 4	Horizontal communications carrier level
Channel 5	Vertical communications carrier level
Channel 6	Combined communications carrier level

Left Event Marker 30-second time pulses

Right Event Marker Boresight camera control pulses

Once-per-second digital printout of doppler shift and time-sequential photographs of antenna beam alignment are also provided at Trinidad. The equipment used for these functions is identical to that used at Floyd as discussed in Paragraph 2.2.7.1.

2.3.7.2 Test Equipment. The following items of test equipment are provided at the Trinidad Site:

1. Distortion Analyzer Hewlett-Packard 330B
2. Frequency Counter, Hewlett Packard 524A with Frequency Converters 525A and 525B
3. Generator, Pulse, Rutherford B-7
4. Generator Sweep Frequency, Kay Vari-Sweep
5. Generator UHF, Hewlett-Packard 616B
6. Meter, Microwave Power Hewlett-Packard 430C
7. Noise Generator, Hot and Cold Body, AIL type 70
8. Oscillator, Hewlett Packard 650A
9. Oscillator, Hewlett Packard 200CD
10. Oscilloscope, Tektronix 515A
11. Receiver, SP-600
12. Recorder, Digital, Hewlett-Packard 560A
13. Recorder Tape, Ampex 960 (two)
14. Tester, Tube Hickok 1575
15. Voltmeter, Vacuum Tube, Hewlett-Packard 400D
16. Voltmeter, Vacuum Tube, Hewlett-Packard 410B
17. Voltmeter, RMS, Ballantine 320
18. Voltmeter, Simpson 270

2.3.8 Radar Mode

The Trinidad facility has a capability for radar-mode pulsed operation to measure monostatic target cross sections. The additional major equipments required for this function are: a pulsing system for the power amplifier, a parametric amplifier and receiver at the transmit frequency, and a duplexing network which uses relative power for the discriminating function rather than frequency separation. The klystron pulser used during operation in the radar mode is described in Paragraph 2.3.3.3.

For performance of the radar duplexer function, during the transmission period a switch must connect the antenna to the transmitter and disconnect it from the receiver. The receiver must be thoroughly isolated from the high-power pulse to avoid damage to the varactor and other components. After transmission, the switch must rapidly disconnect the transmitter and reconnect the receiver to the antenna. The switching time required is a function of the minimum target range of interest. Switching must be accomplished with very little power loss during transmission or reception.

The narrowband requirements of the system would permit the use of a branching type duplexer and a balanced duplexer would also fulfill the needs. However, since neither TR or ATR tubes had been developed in this range an expensive development program would have been required. Since the contracting agency had available a ferrite circulator constructed with WR-430 waveguide, the only necessary development work was a low power TR tube (crystal protector) for use with the supplied ferrite circulator to provide the transmit-receive switching function.

Although the ferrite-circulator solution has considerably less power handling capability than the other techniques and also requires water cooling, which the others do not, it has the advantage that it performs an isolating function between the power amplifier and the transmission system and antenna. This will be explained in the following description of operation.

In his coverage of ferrite devices, Bowness¹⁸ would class this as a four-port circulator duplexer utilizing the nonreciprocal phase-shift characteristics of ferrites. The nonreciprocal phase-shift ferrite duplexer is made up of a folded magic-T, two waveguide sections with magnetically biased ferrite material, a short slot hybrid, and an absorptive load in one

port. A sketch of this type of duplexer is shown in Figure 2-34 and it illustrates the basic configuration of the device used.

Figures 2-35(a) and 2-35(b) depict the signal paths through the duplexer for the transmit energy and the receive energy, respectively. The device functions as follows: the transmitter power enters the folded magic-T and divides into two paths, both identical in phase and amplitude. As the two signals pass through the two halves of the guide containing the magnetically biased ferrite material, one signal is advanced 45° in phase while the second is retarded by an equivalent amount. The two signals leave the ferrite sections and enter a short-slot hybrid where they combine constructively in the antenna arm and are cancelled in the load arm. On reception (Figure 2-44b), signals from the antenna arm enter the short slot hybrid. On the direct short path the phase is undisturbed until it passes the ferrite slab, where it is advanced 45° . The energy traveling the longer path is first retarded 90° in the short slot and then an additional 45° at the ferrite slab. Signals leaving the ferrite sections and entering the attached sections of the folded magic-T are then equal in amplitude and 180° out of phase. Hence they combine constructively in the E, or receiver, arm and cancel in the H, or transmit, arm. The diode protector TR protects the receiver both from leakage from the transmitter arm and the reflected power from the antenna arm during transmission.

The circulator-duplexer acts to isolate the transmit arm from reflections in the antenna line. Behaving in the same manner as for a received signal, the reflected energy combines into the E arm of the magic-T. This energy is reflected from the ionized TR tube and travels back to the circulator to be combined, in this case, into the dummy load arms. Therefore, mismatches in the transmission line past the duplexer are essentially unseen by the transmitter.

For reception of the pulse echoes in the radar mode of operation, the 2270 mc parametric amplifiers² and converters utilized on the original simplex circuit were moved to Trinidad, and have been installed in an equipment dolly in the equipment building. These parametric amplifiers and converters can be used in two ways: (1) with one of the site SP-600 communications receivers (requiring manual tracking of the doppler shift), or (2) if the reverse path is not being simultaneously utilized, with one channel of the regular doppler-tracking receiver. An overall noise figure of approximately 4 db, together with a line and duplexer loss of 3.5 db, yield a system noise temperature of approximately 1440°K.

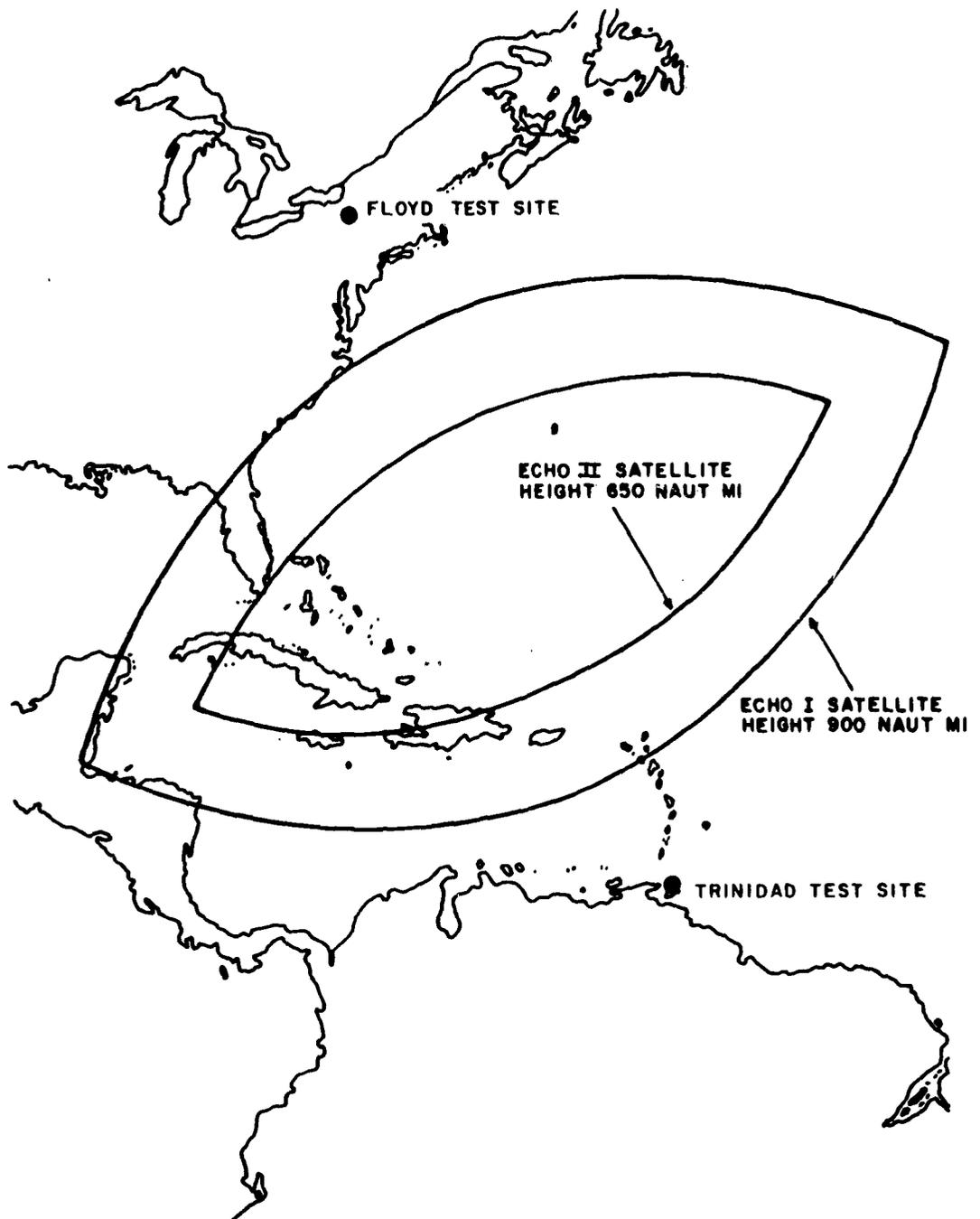


Figure 2-1. Areas of Mutual Visibility, Floyd-Trinidad Path

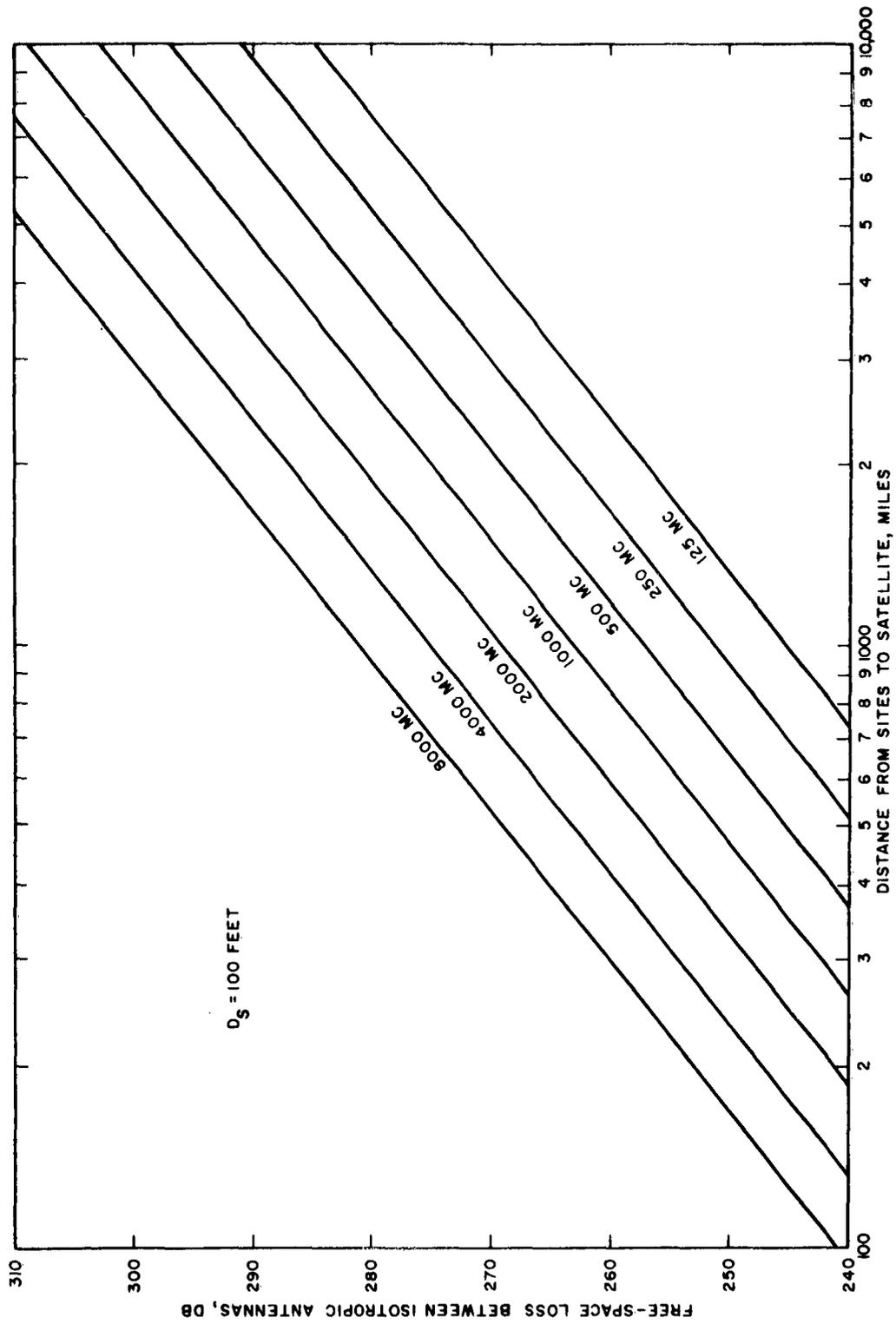


Figure 2-2. Path Loss Between Isotropic Antennas on the Ground vs. Distance

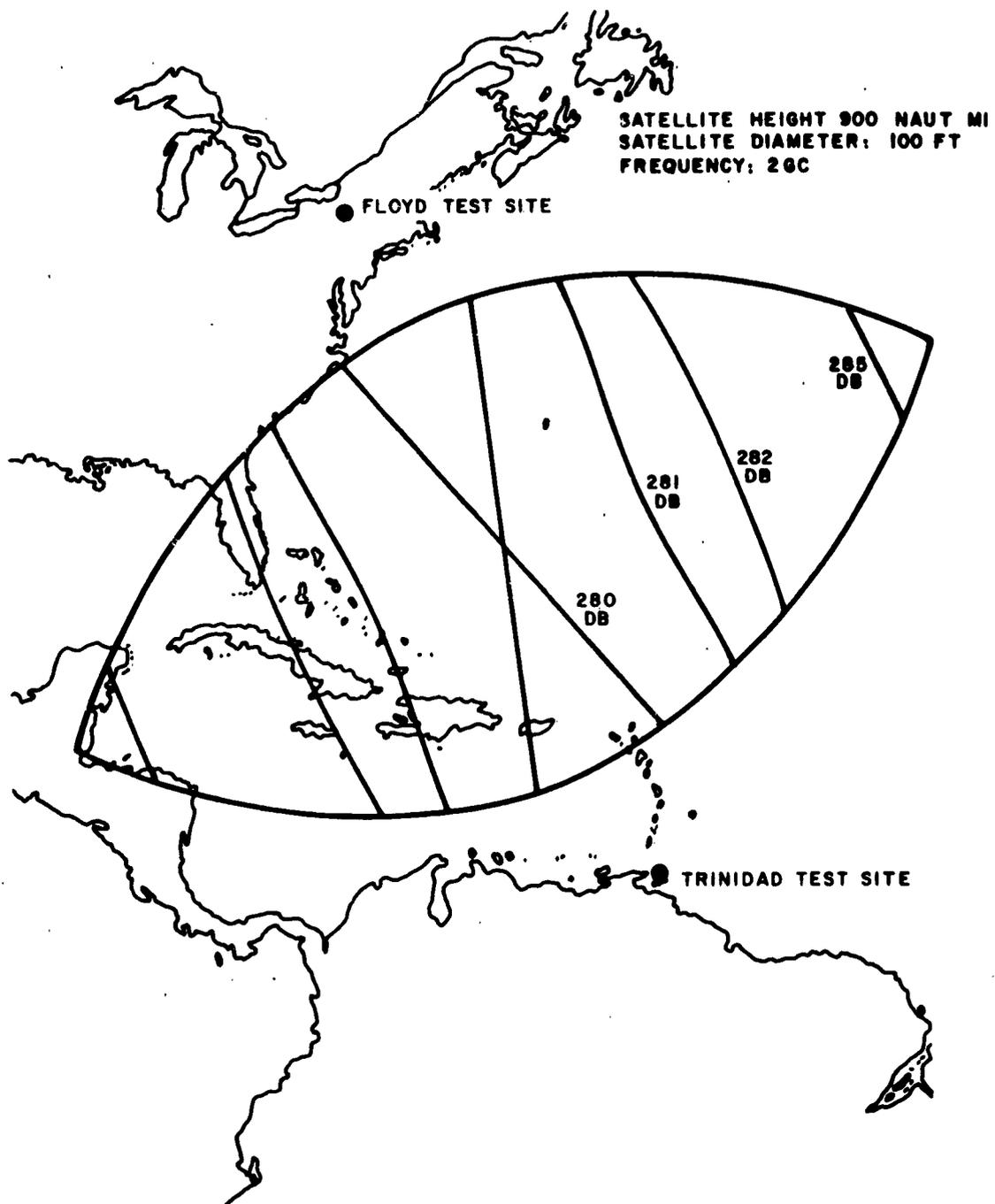


Figure 2-3. Path Loss Profiles, Floyd-Trinidad Path, Echo I Satellite

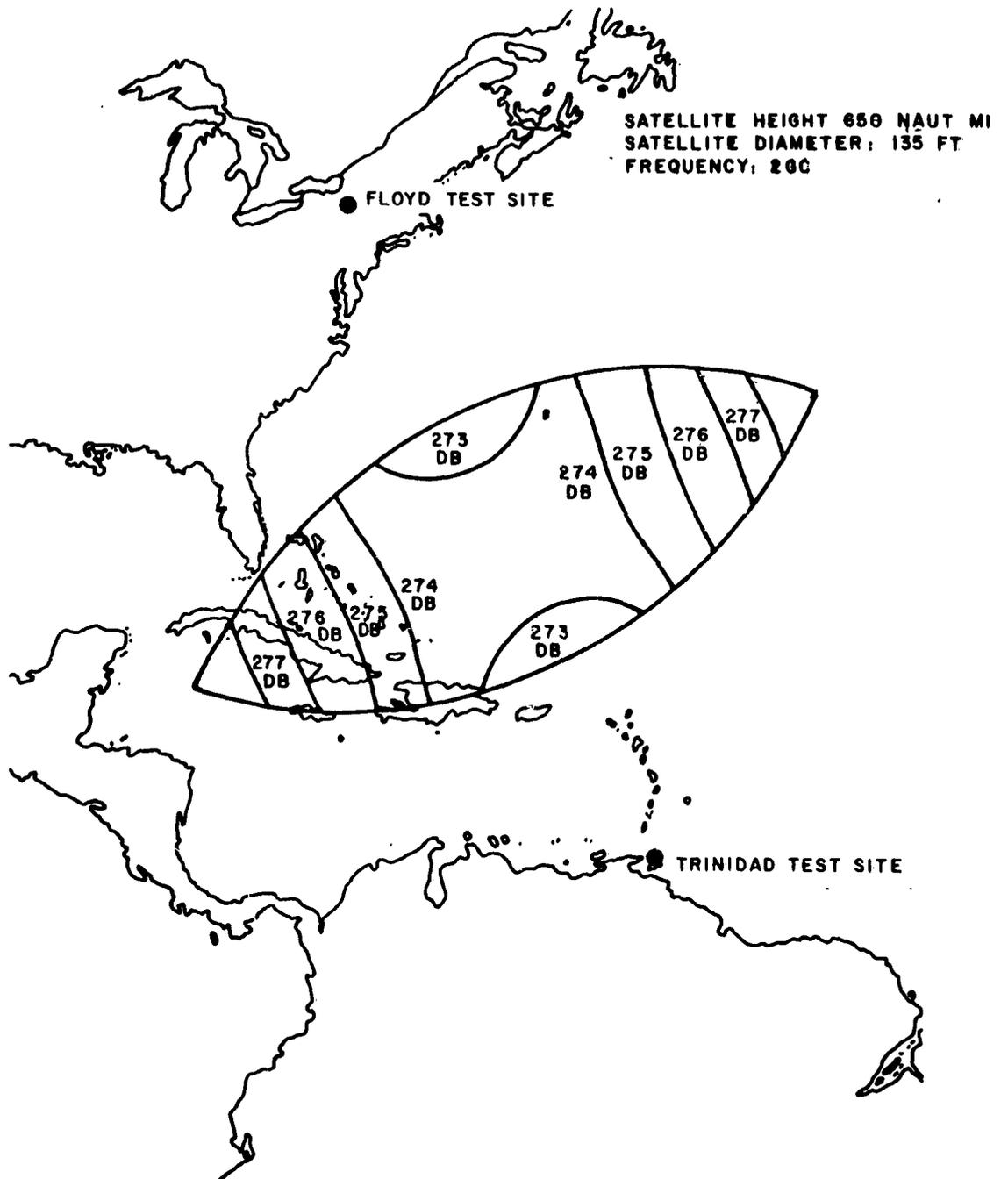


Figure 2-4. Path Loss Profiles, Floyd-Trinidad Path, Echo II Satellite

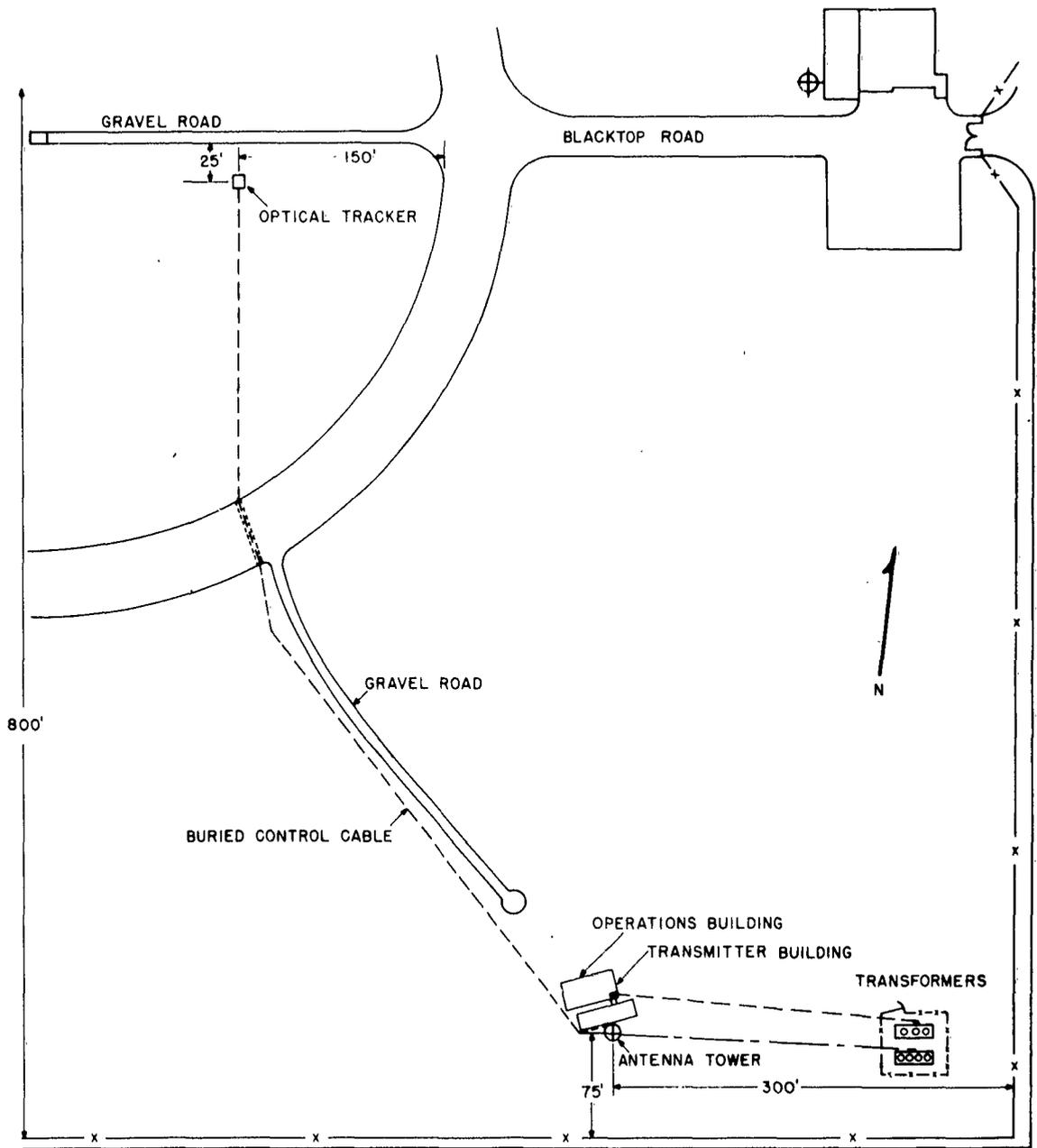
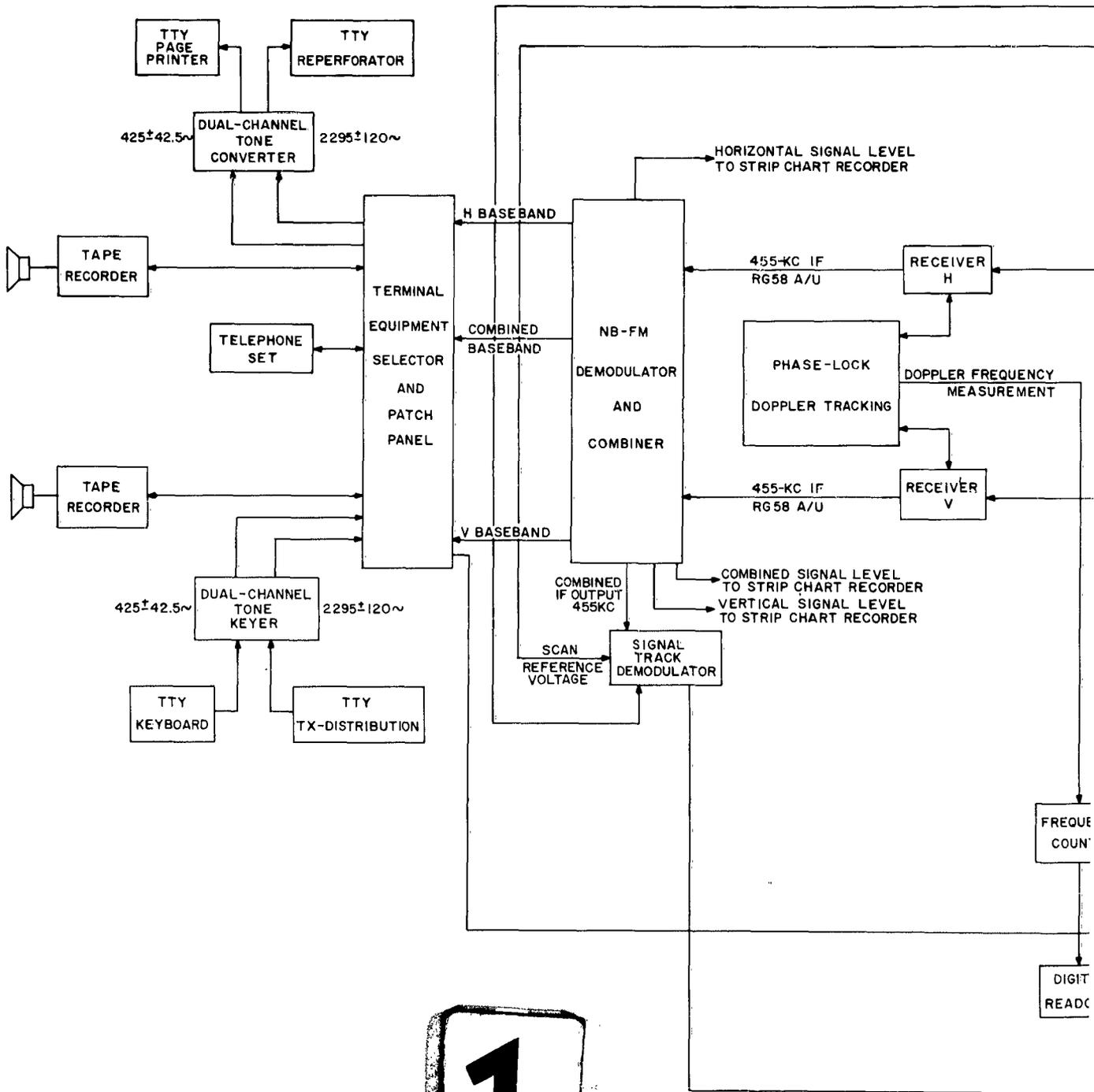
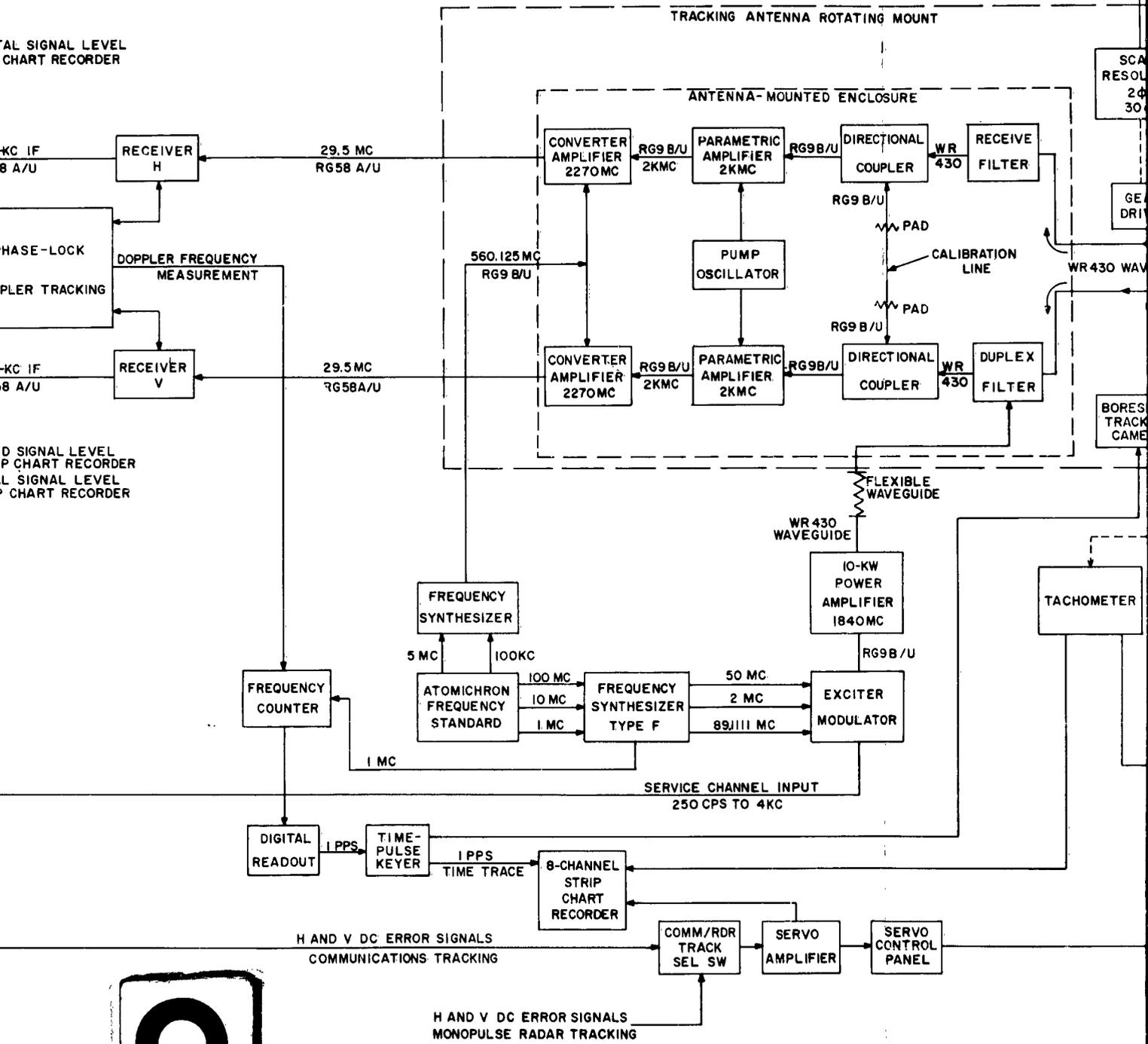


Figure 2-5. Floyd Site Plot Plan





2

Figure 2-6. Floyd S

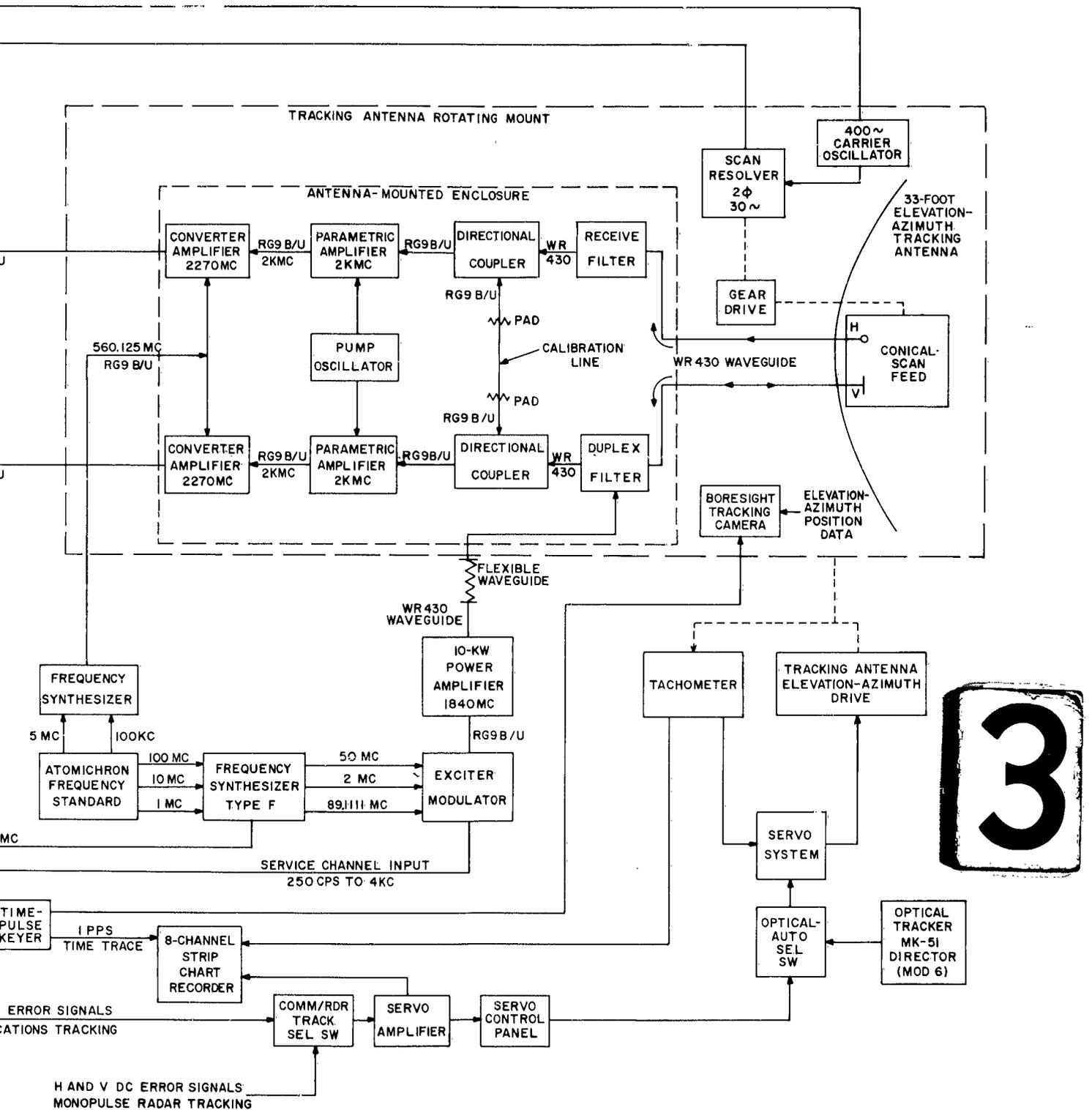


Figure 2-6. Floyd System Block Diagram

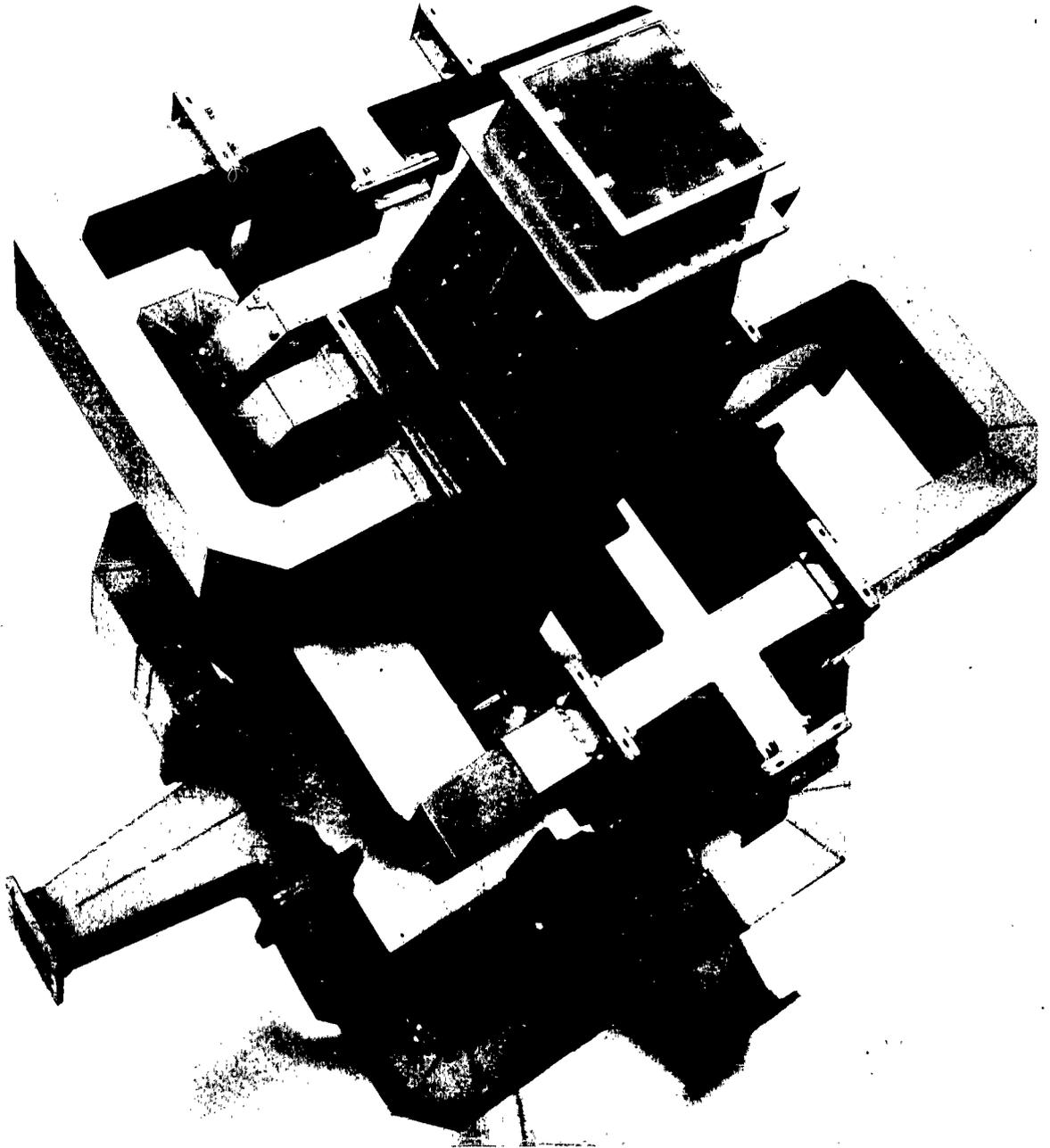


Figure 2-7. Floyd Dual-Polarization 2-GC Tracking Feed

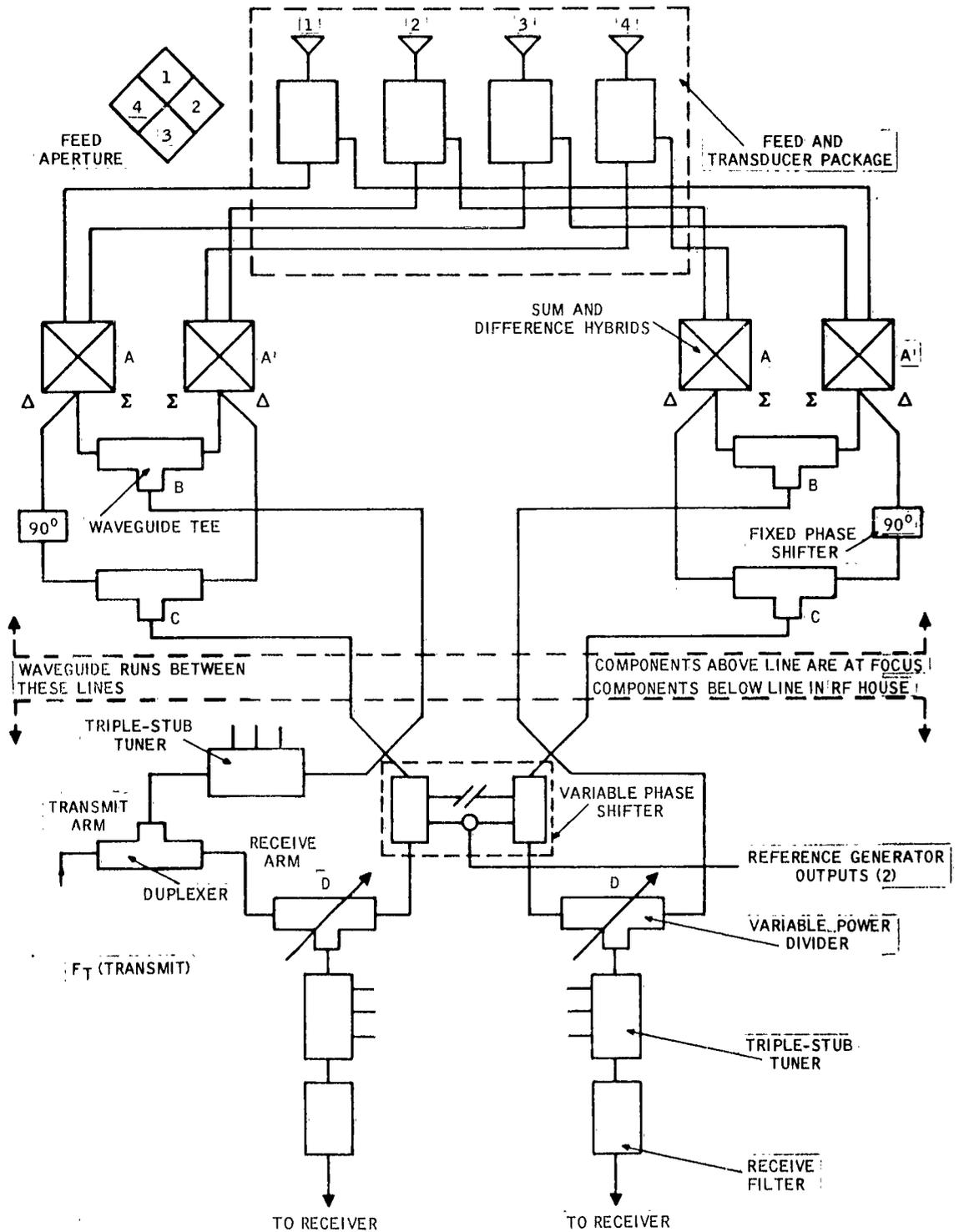


Figure 2-8. Floyd P-CC Feed System Block Diagram

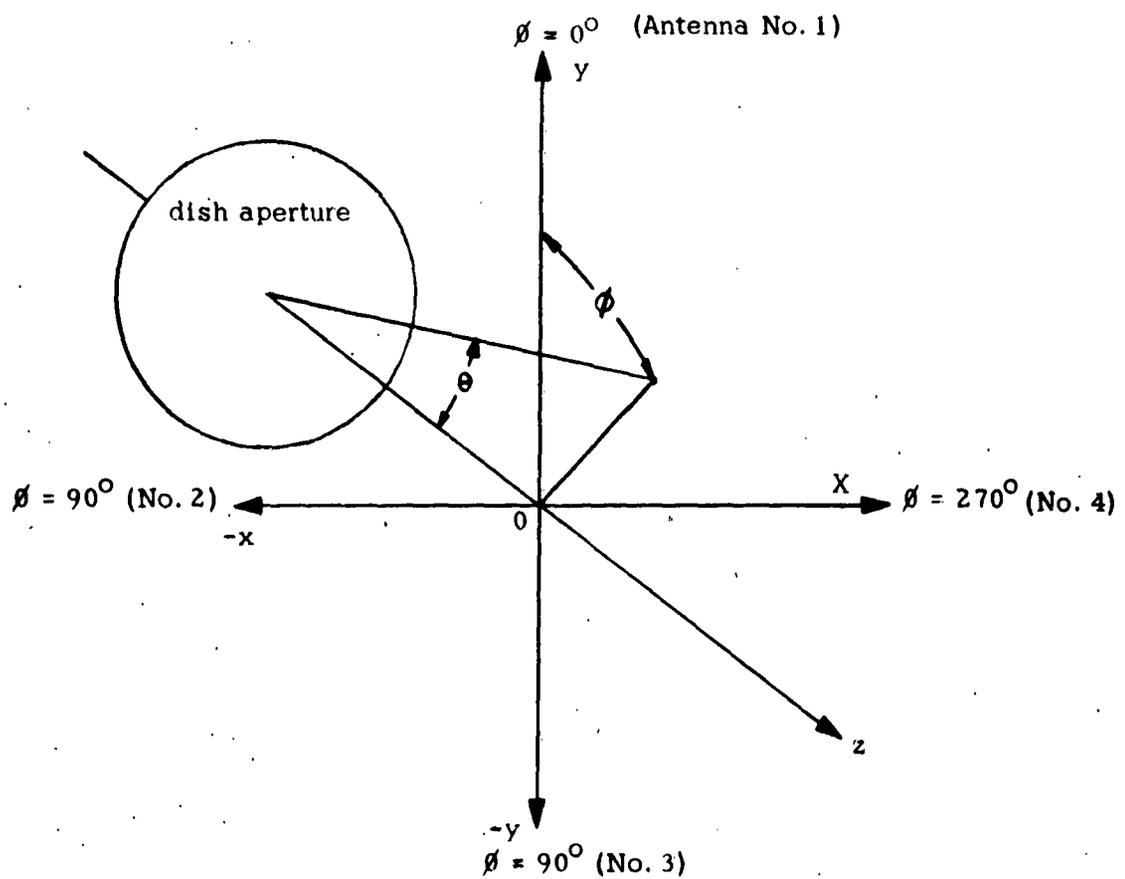
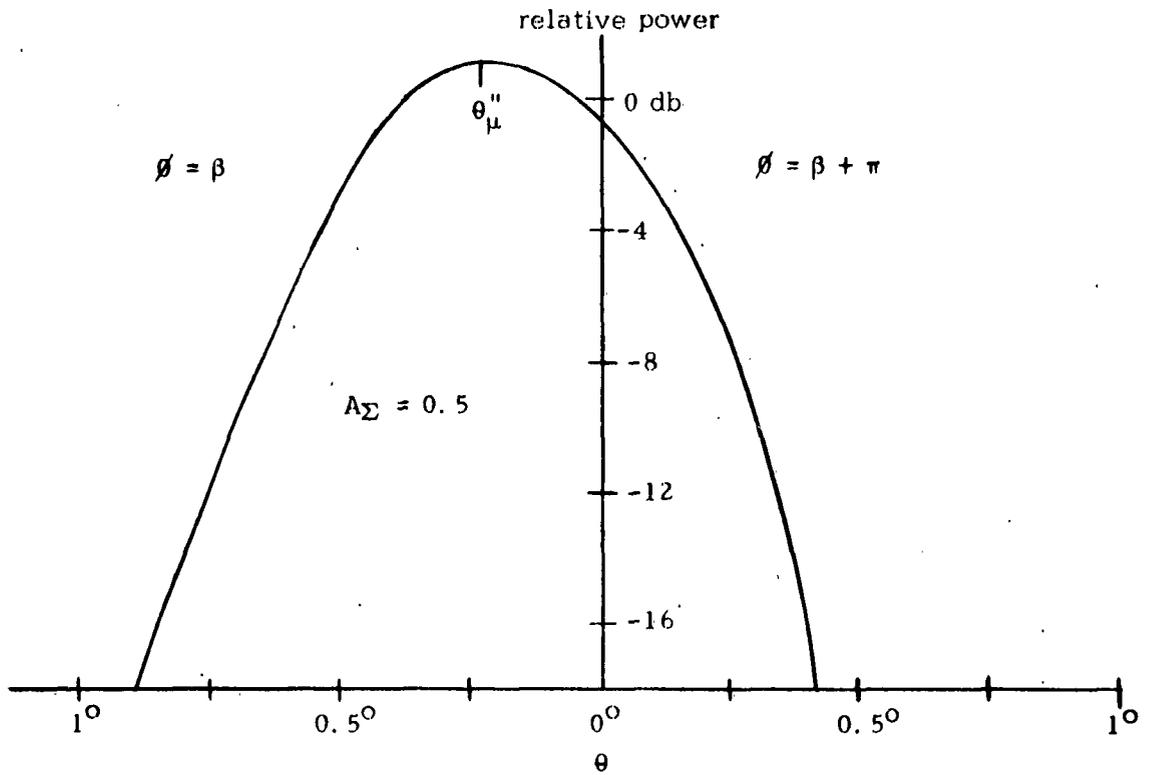
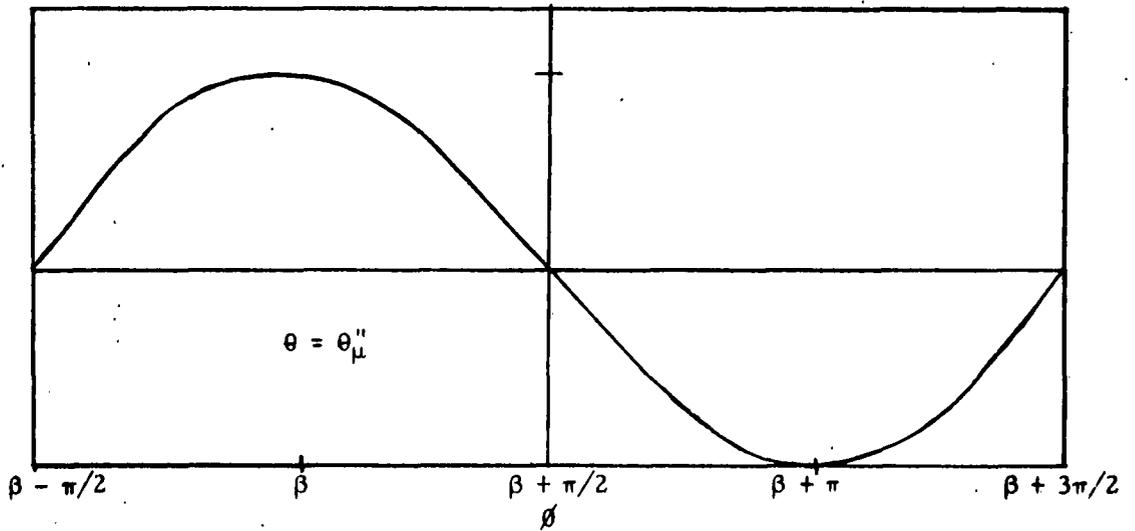


Figure 2-9. Floyd Antenna Coordinate System



(a) Power Pattern at Receiver Output (θ variable)



(b) Power Pattern at Receiver Output (ϕ variable)

Figure 2-11. Synthetic Scan Patterns

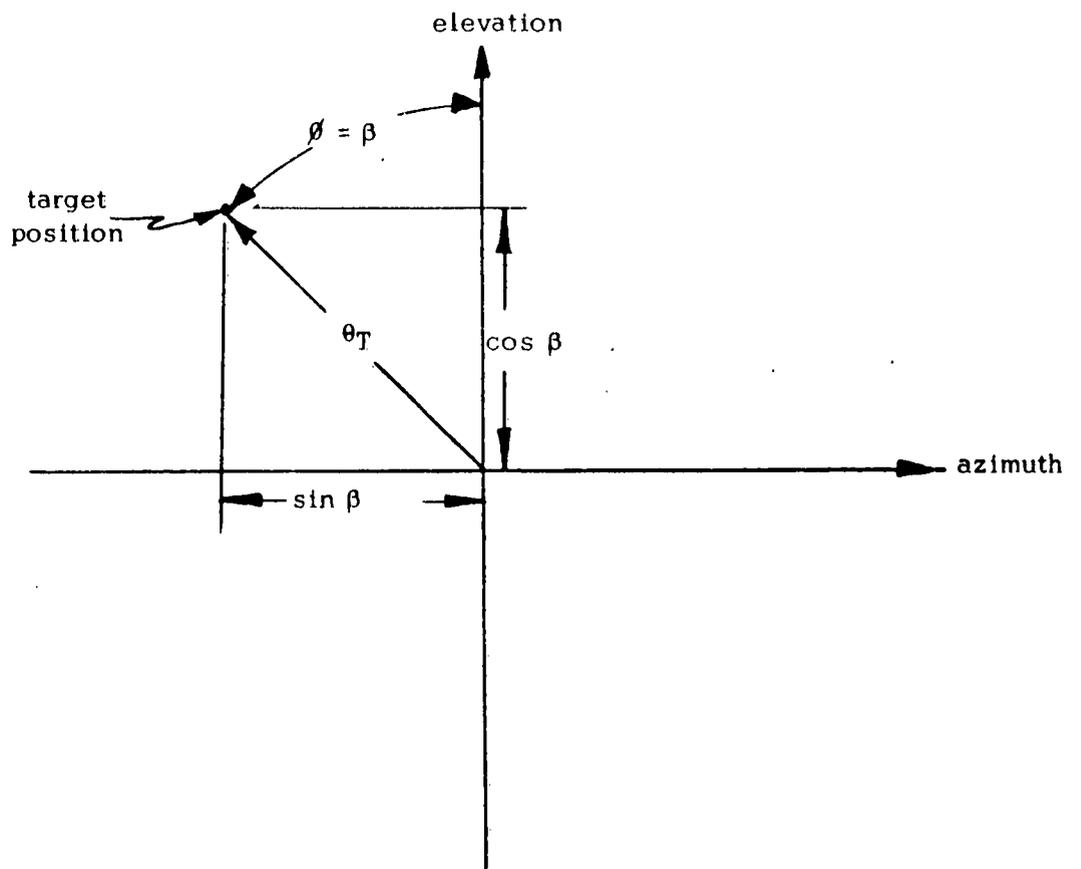


Figure 2-12. Target Coordinates

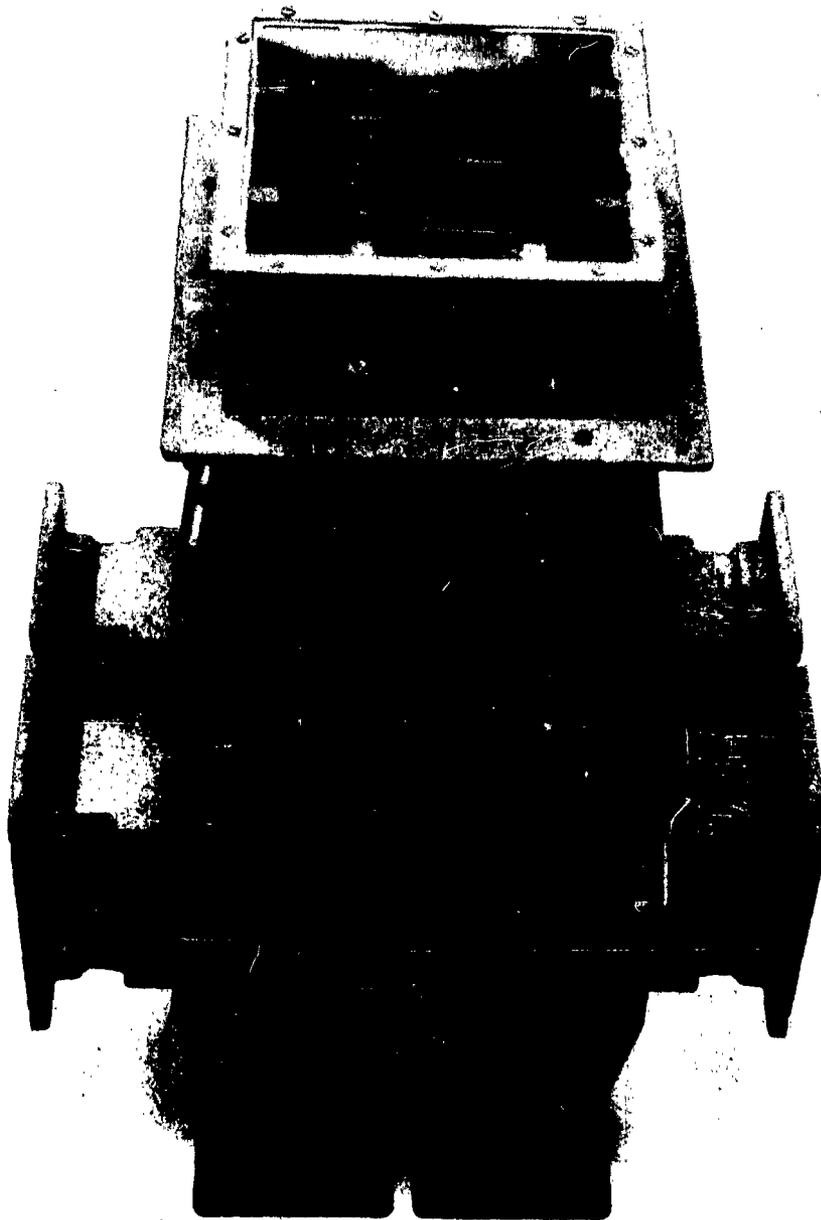


Figure 2-13. Dual-Polarized, Four-Channel Antenna Feed for 1700 to 2400 MC



Figure 2-14. Dual-Channel Fox Phase Shifter, Interior View

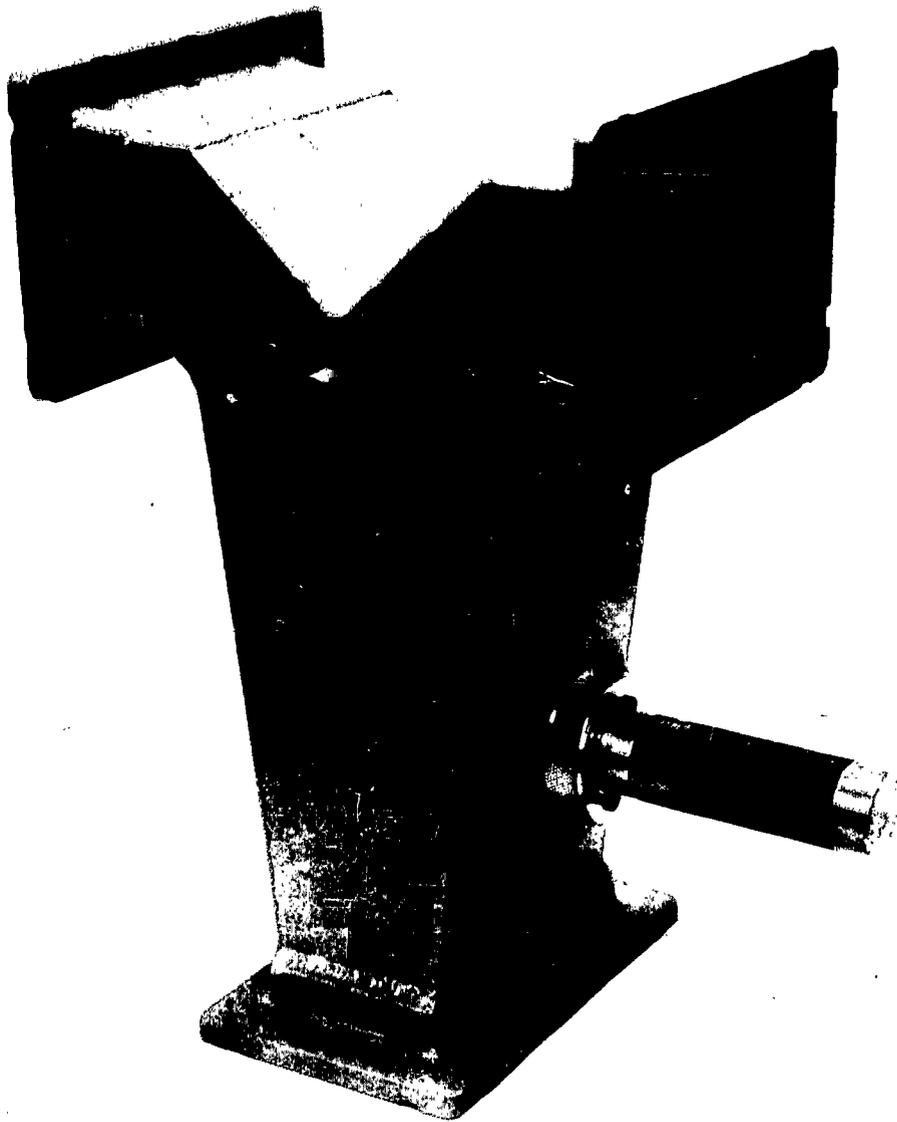


Figure 2-15. Variable Power Divider

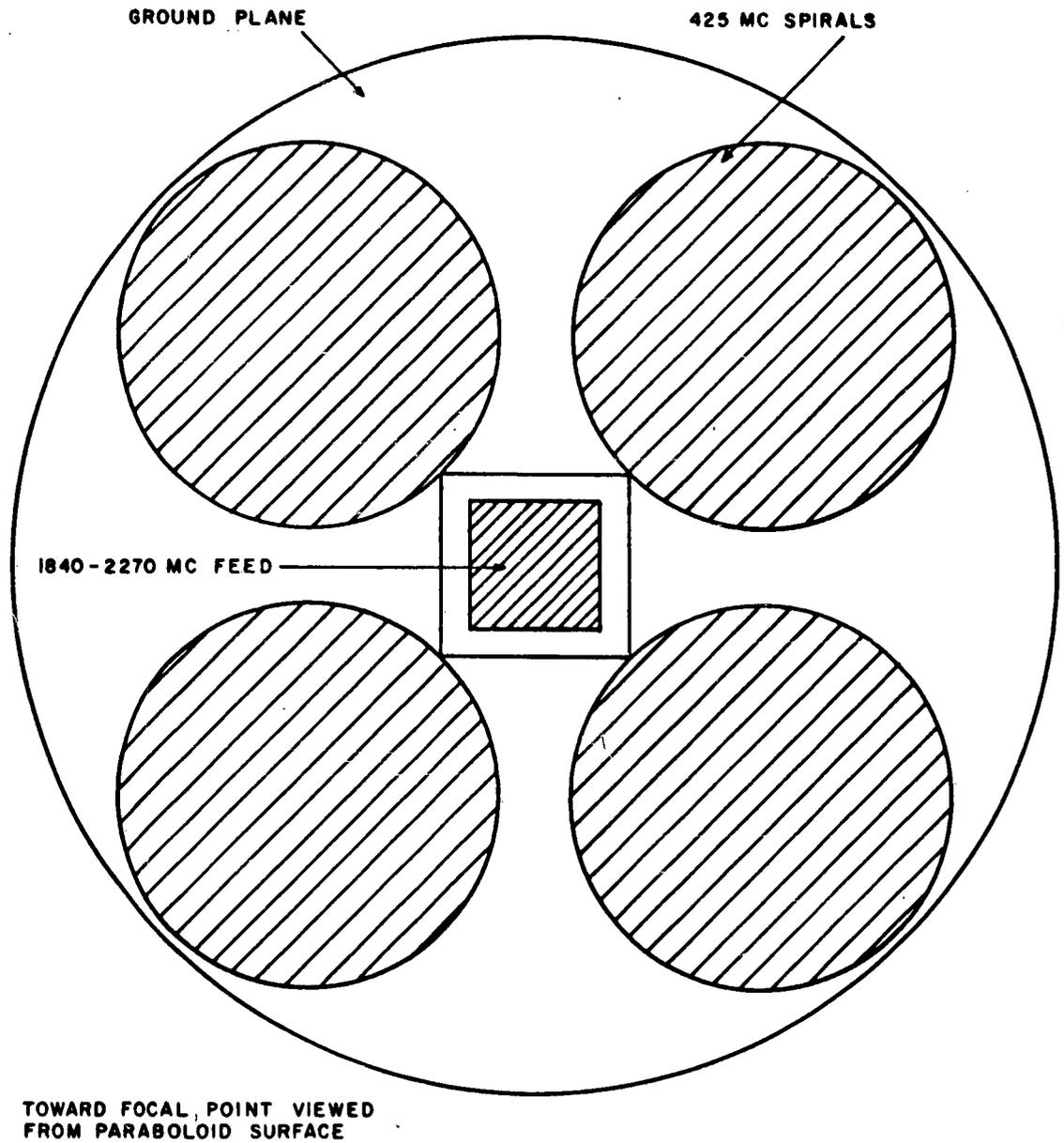


Figure 2-16. Floyd Feed Cluster Configuration

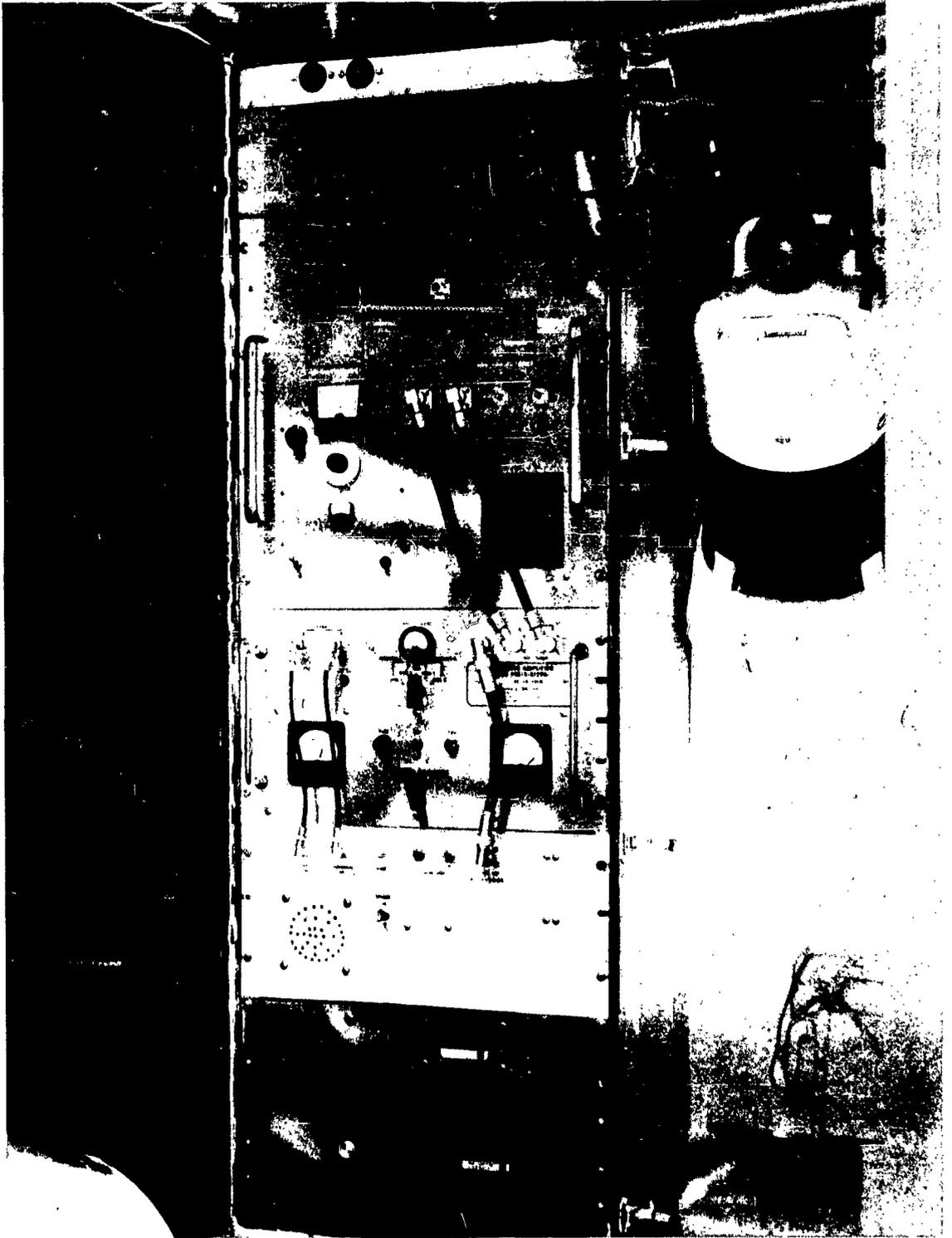


Figure 2-17. Trinidad Parametric Amplifier and Converter Installation

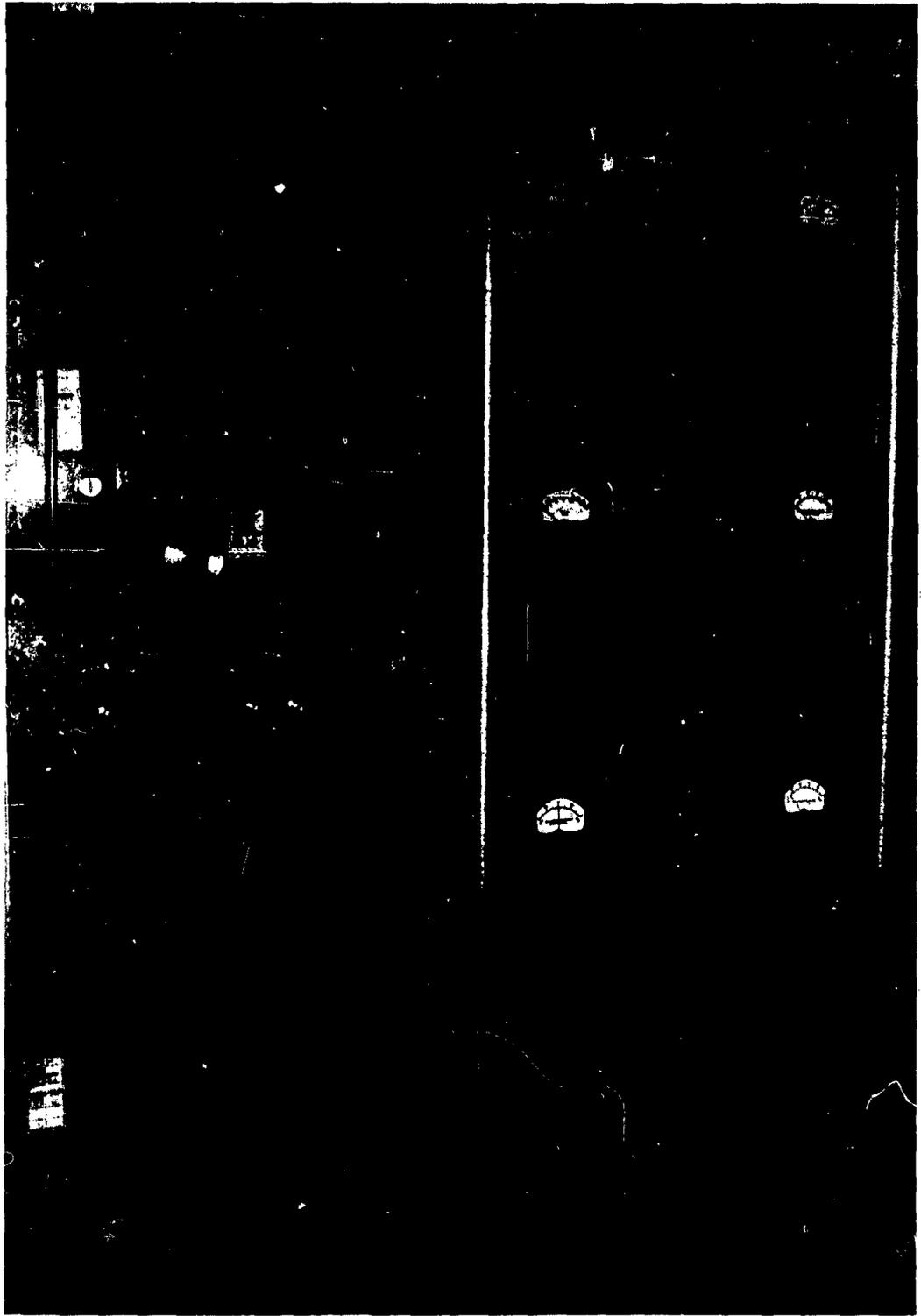


Figure 2-18. Doppler Tracking Receiver

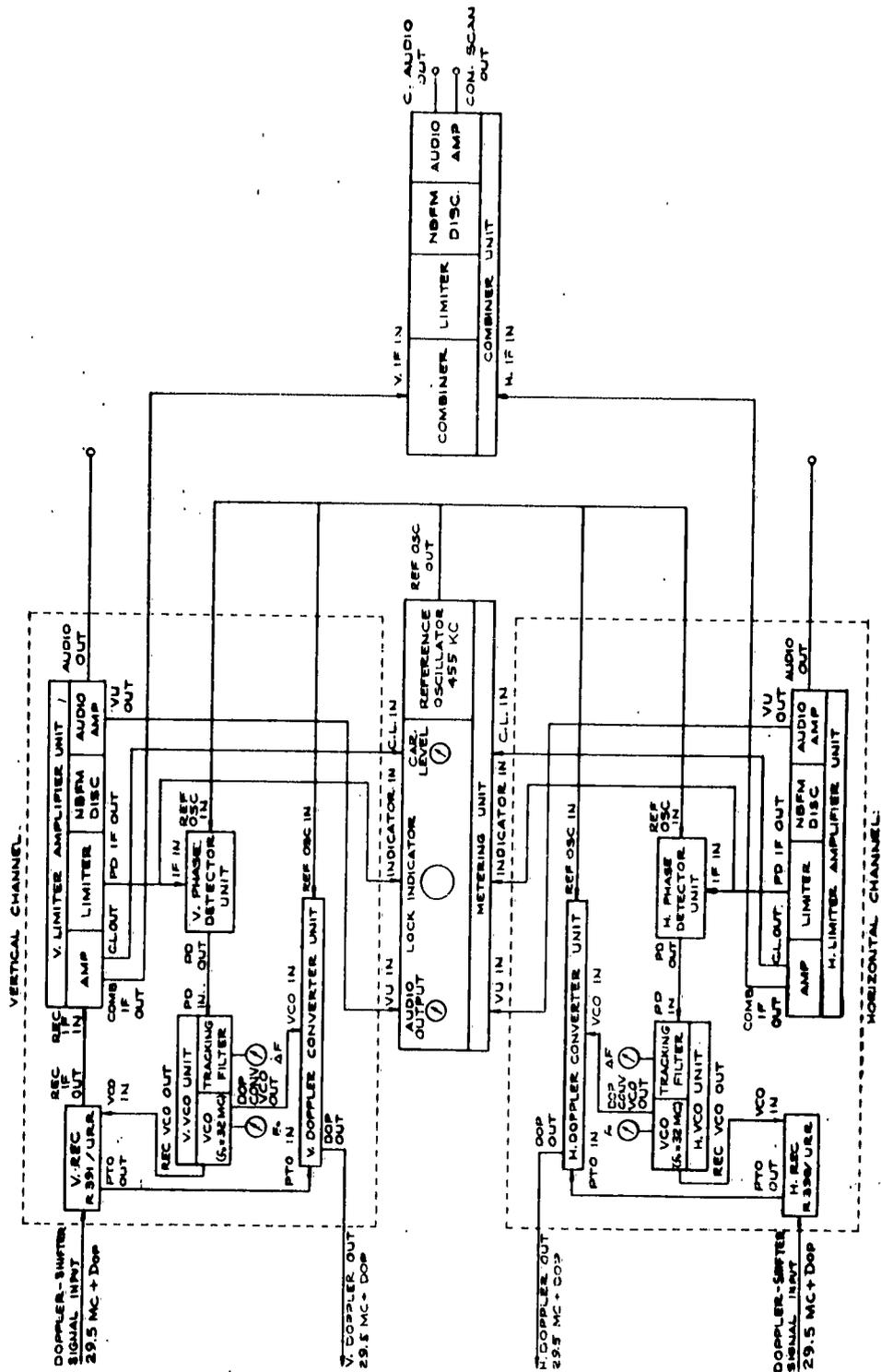


Figure 2-19. Doppler Tracking Receiver Block Diagram

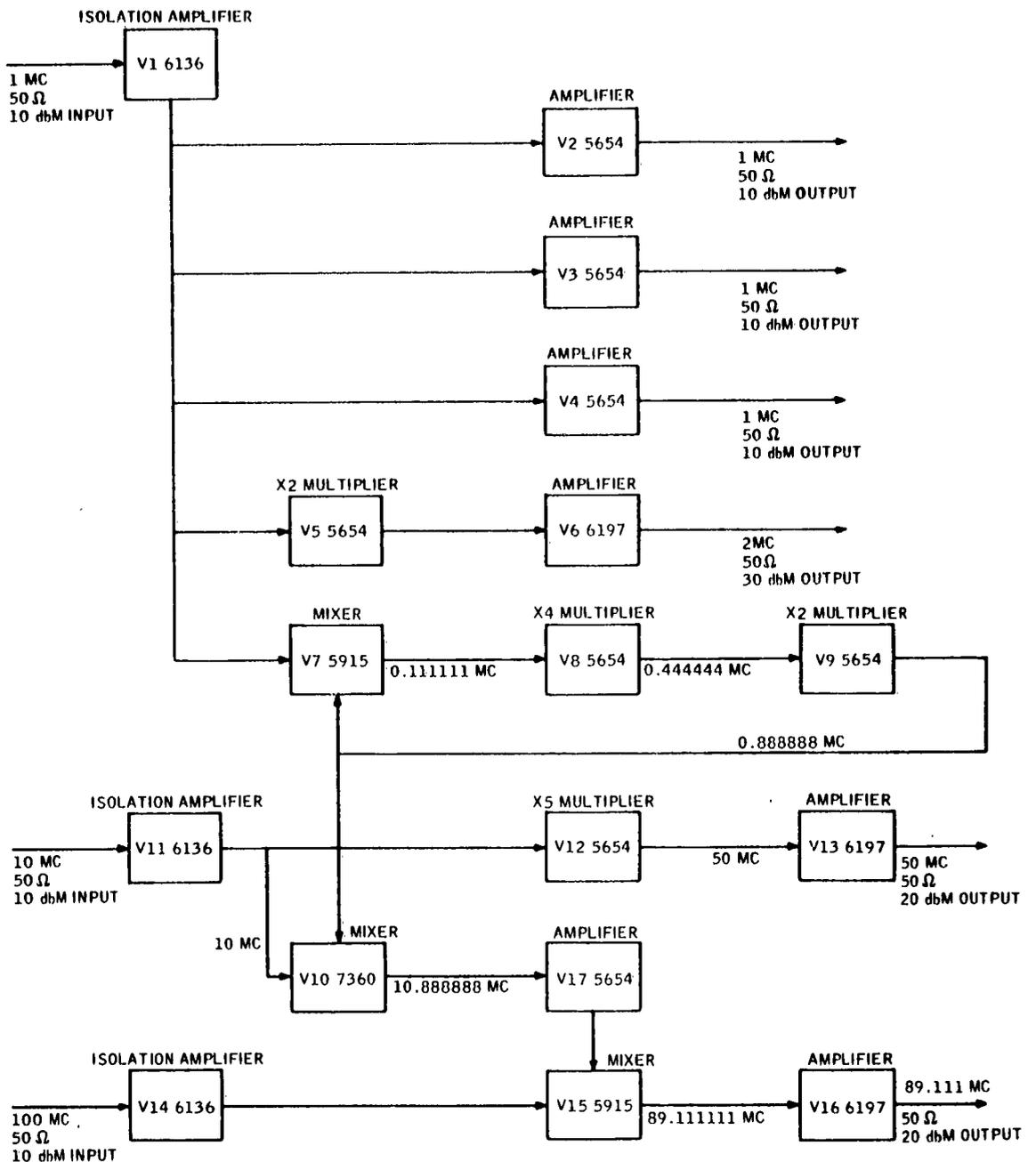


Figure 2-20. Page Frequency Synthesizer, Type F, Block Diagram



Figure 2-21. Boresight Camera Installation

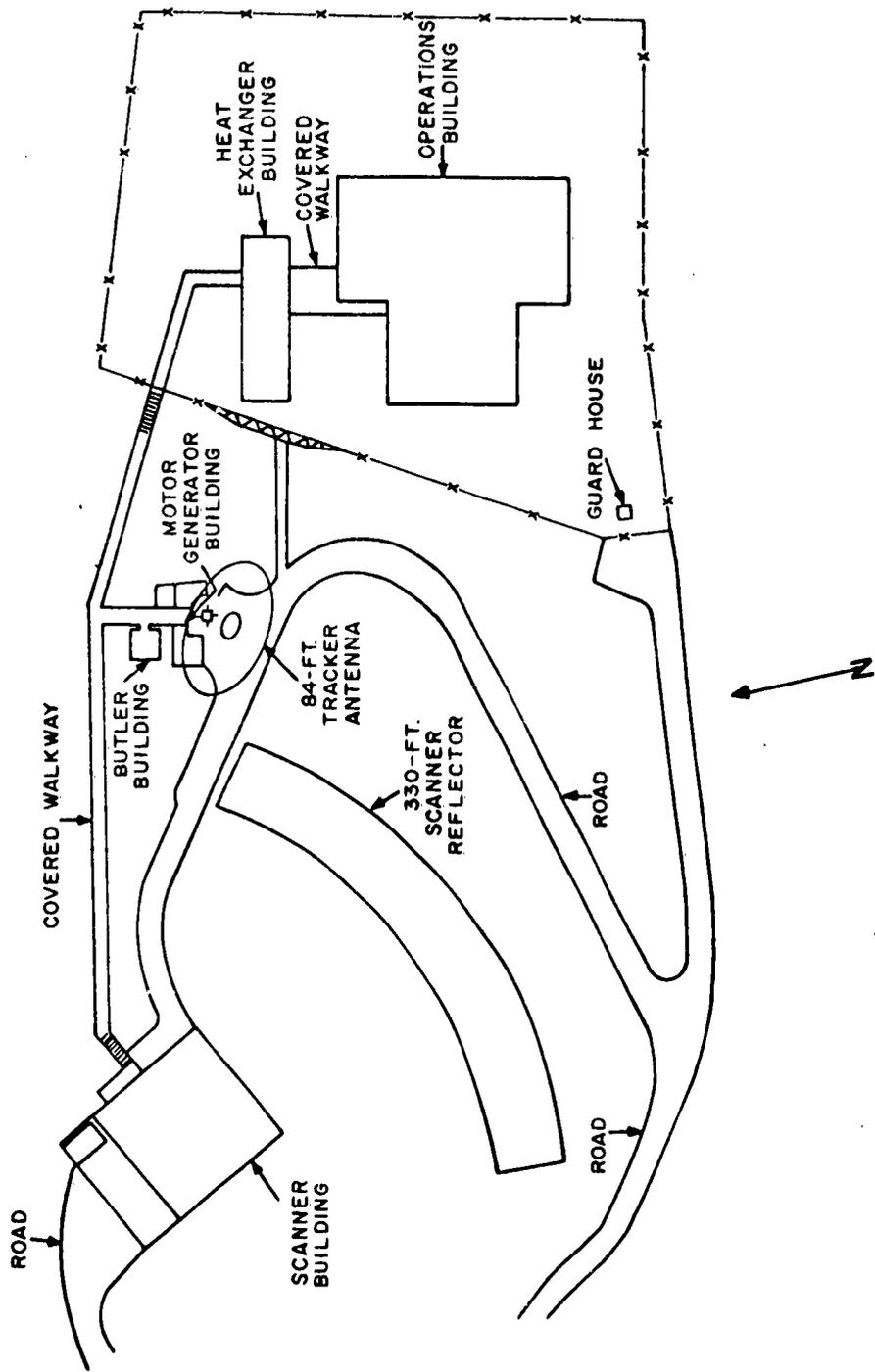
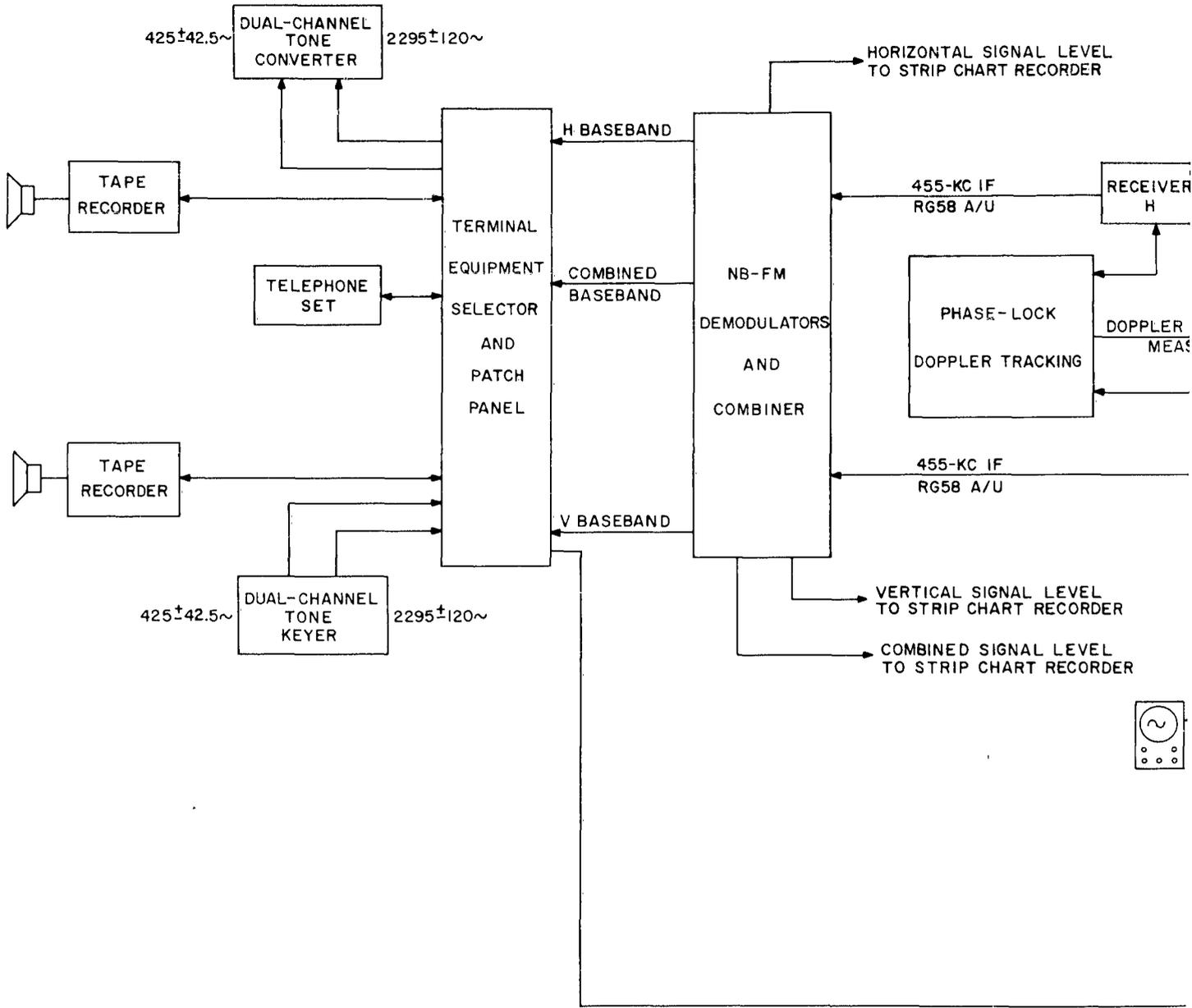
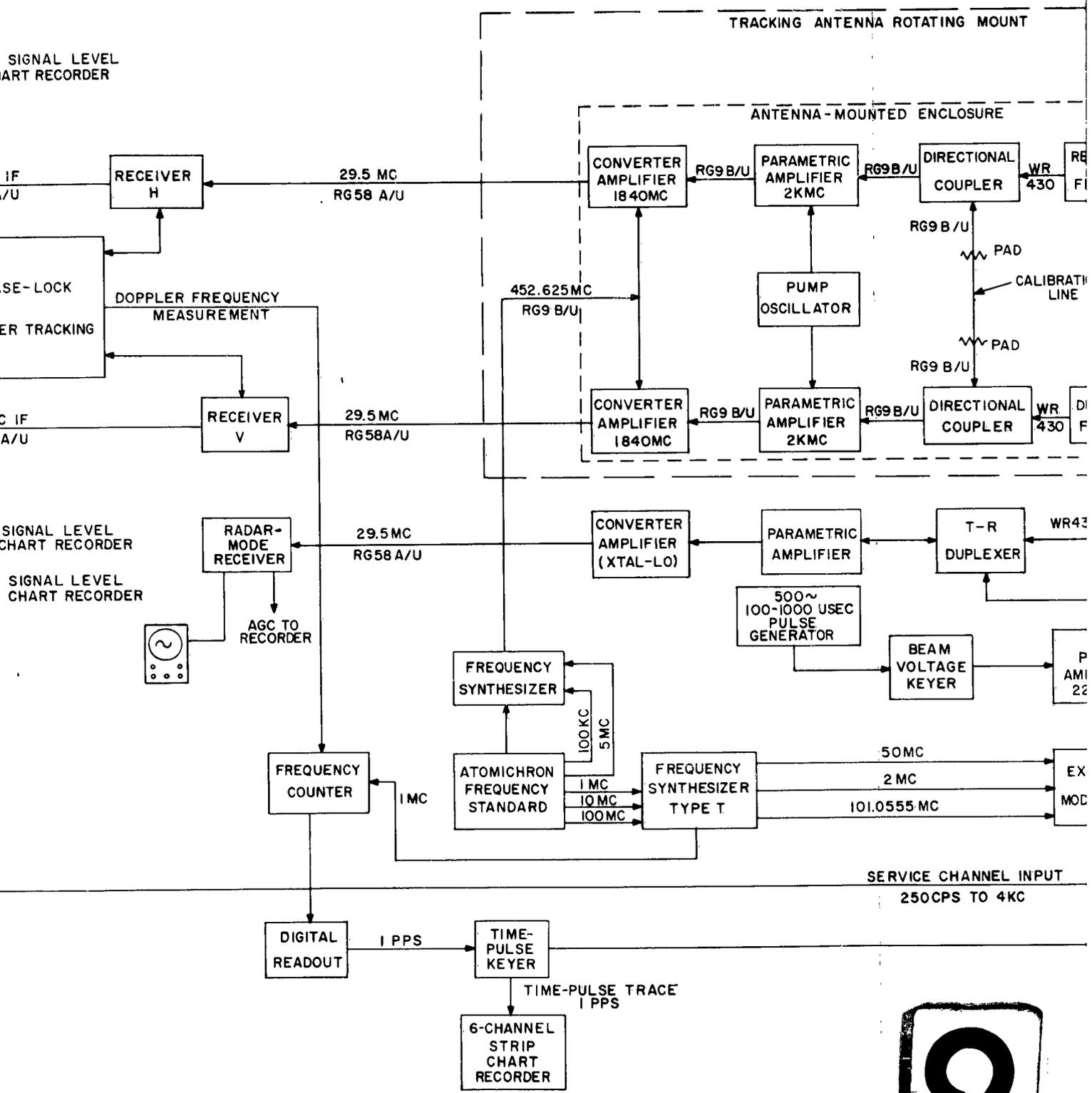
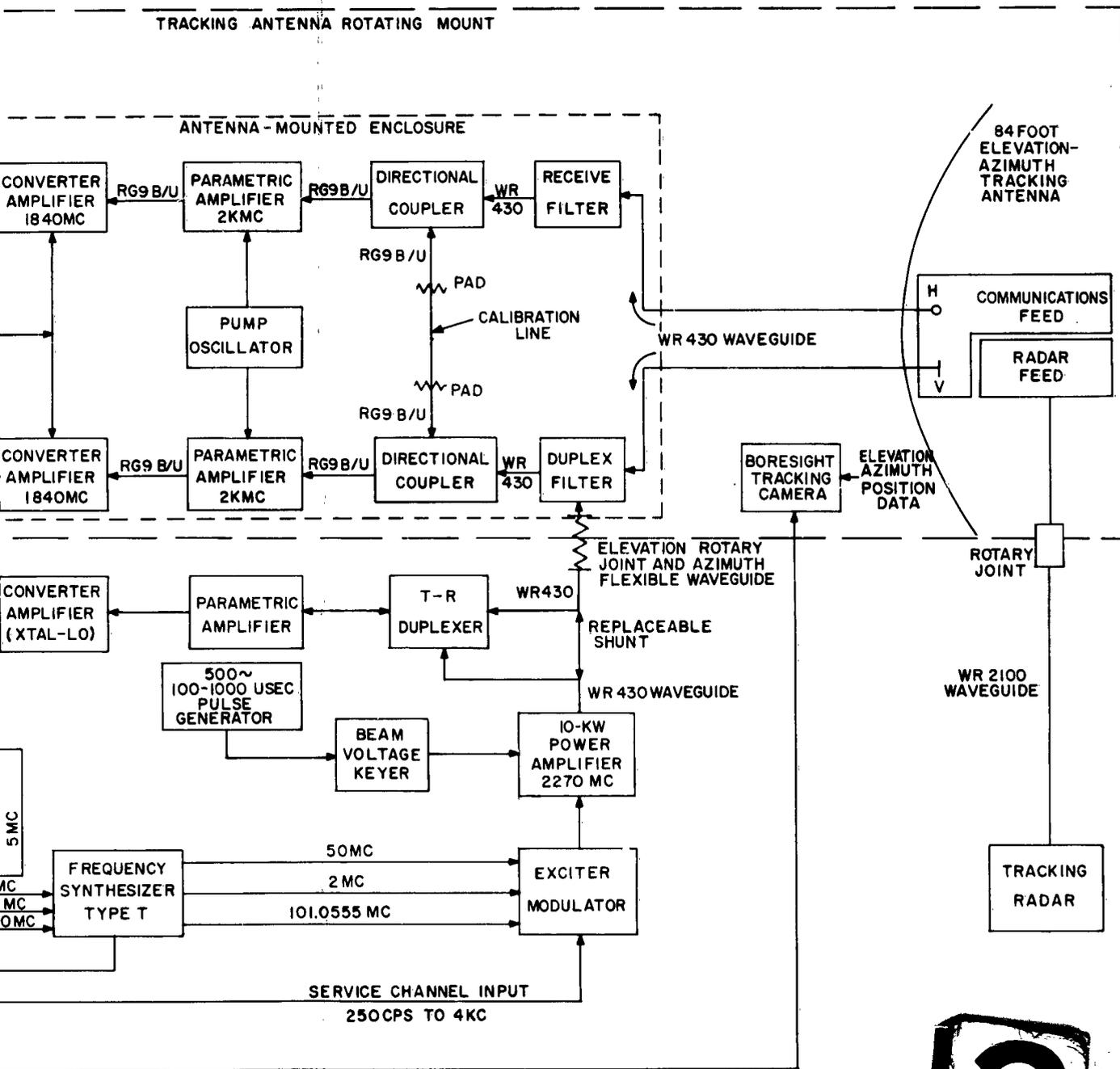


Figure 2-22. Trinidad Site Plot Plan



1





SE TRACE
PPS



Figure 2-23. Trinidad System Block Diagram

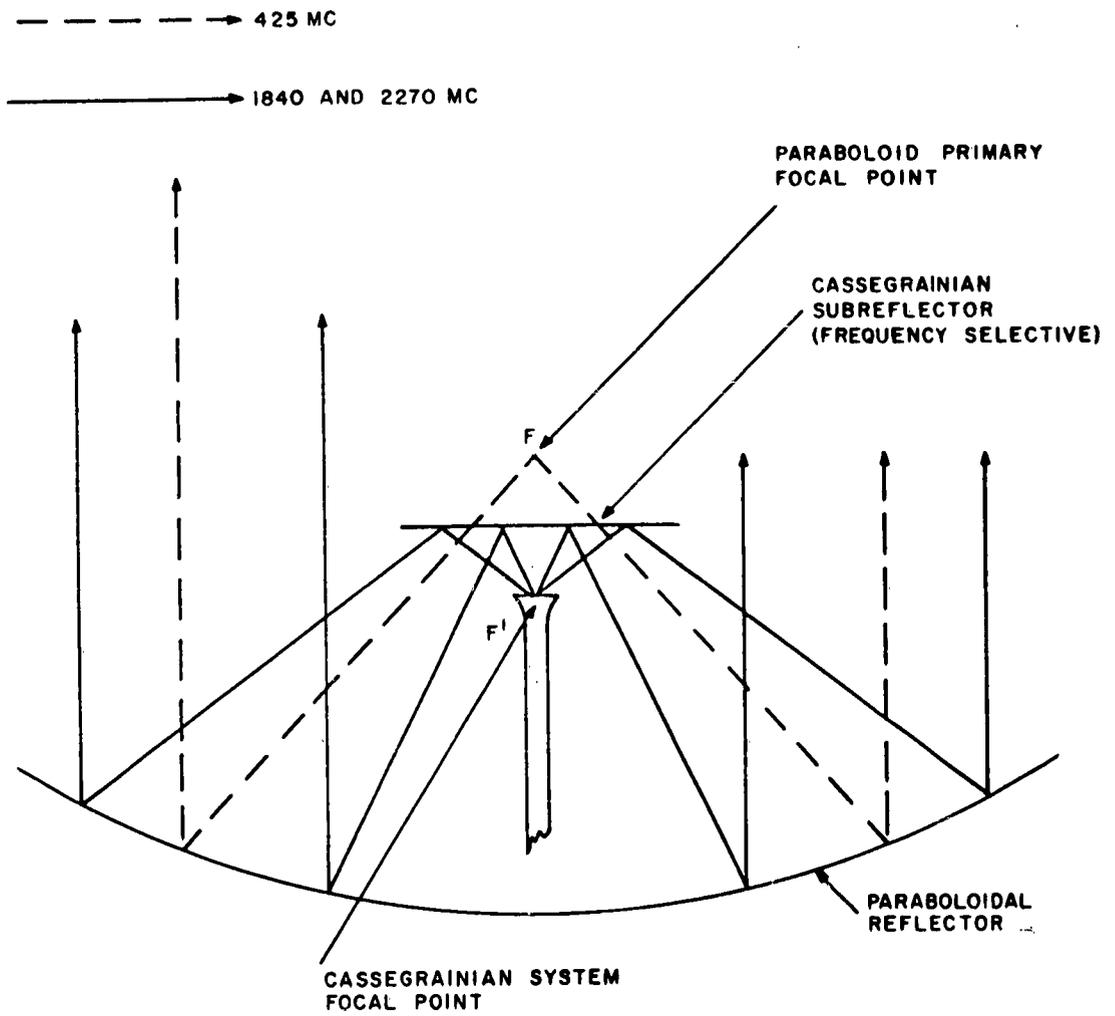


Figure 2-24. Trinidad Dual-Frequency Antenna System

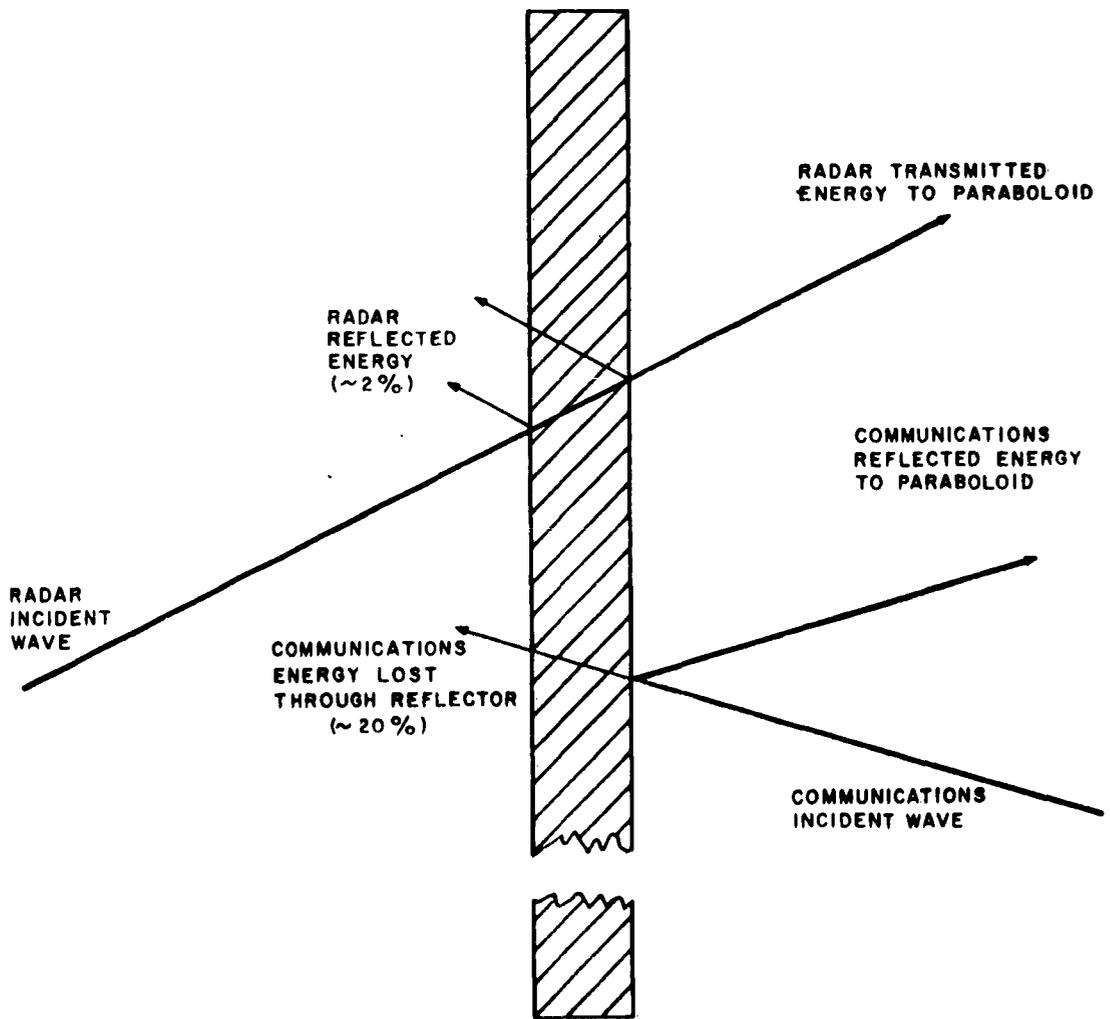


Figure 2-25. Frequency Selective Reflector, Basic Principle of Operation

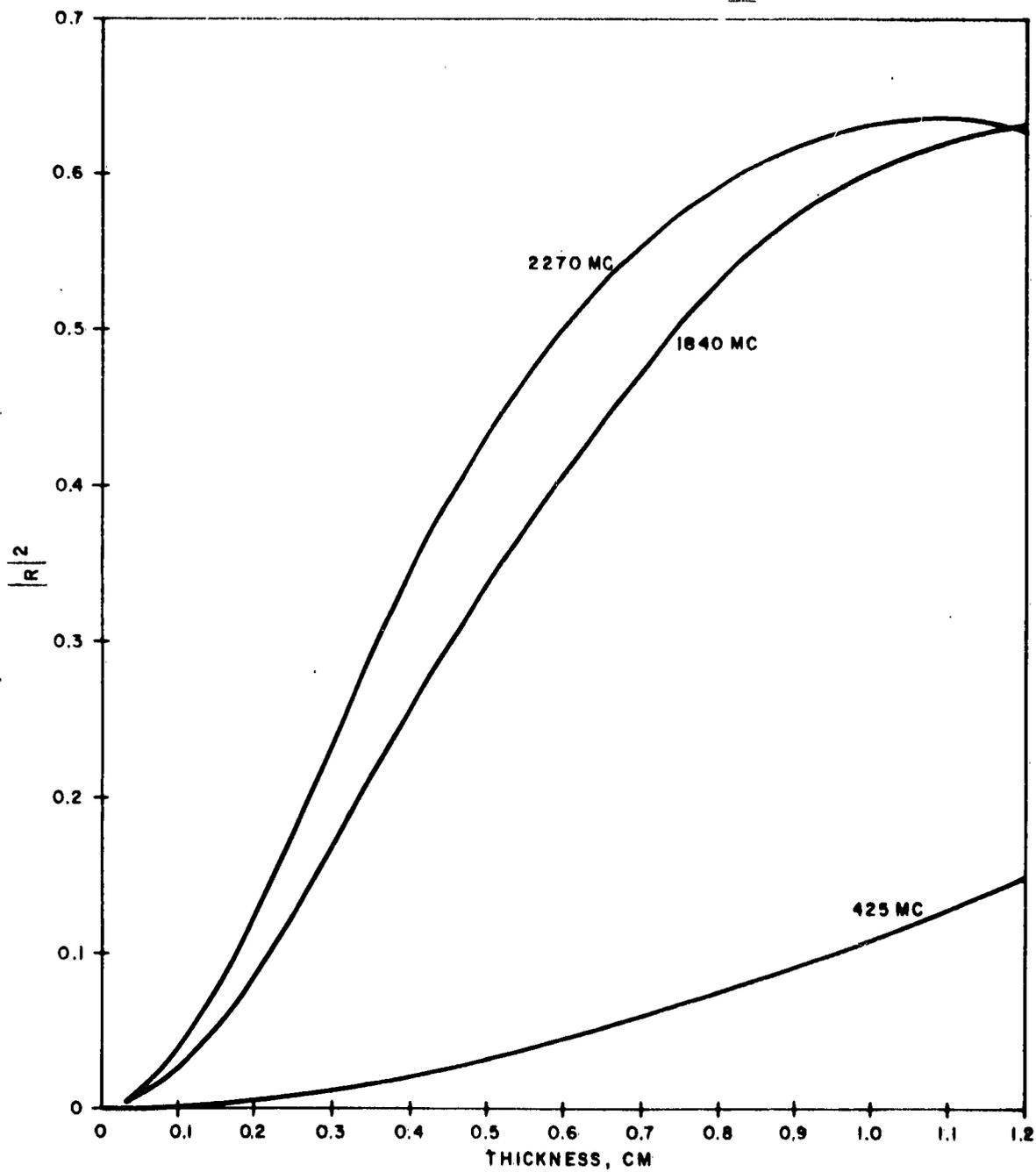


Figure 2-26. Reflection-Coefficient Magnitude vs. Slab Thickness for Dielectric Constant of 9

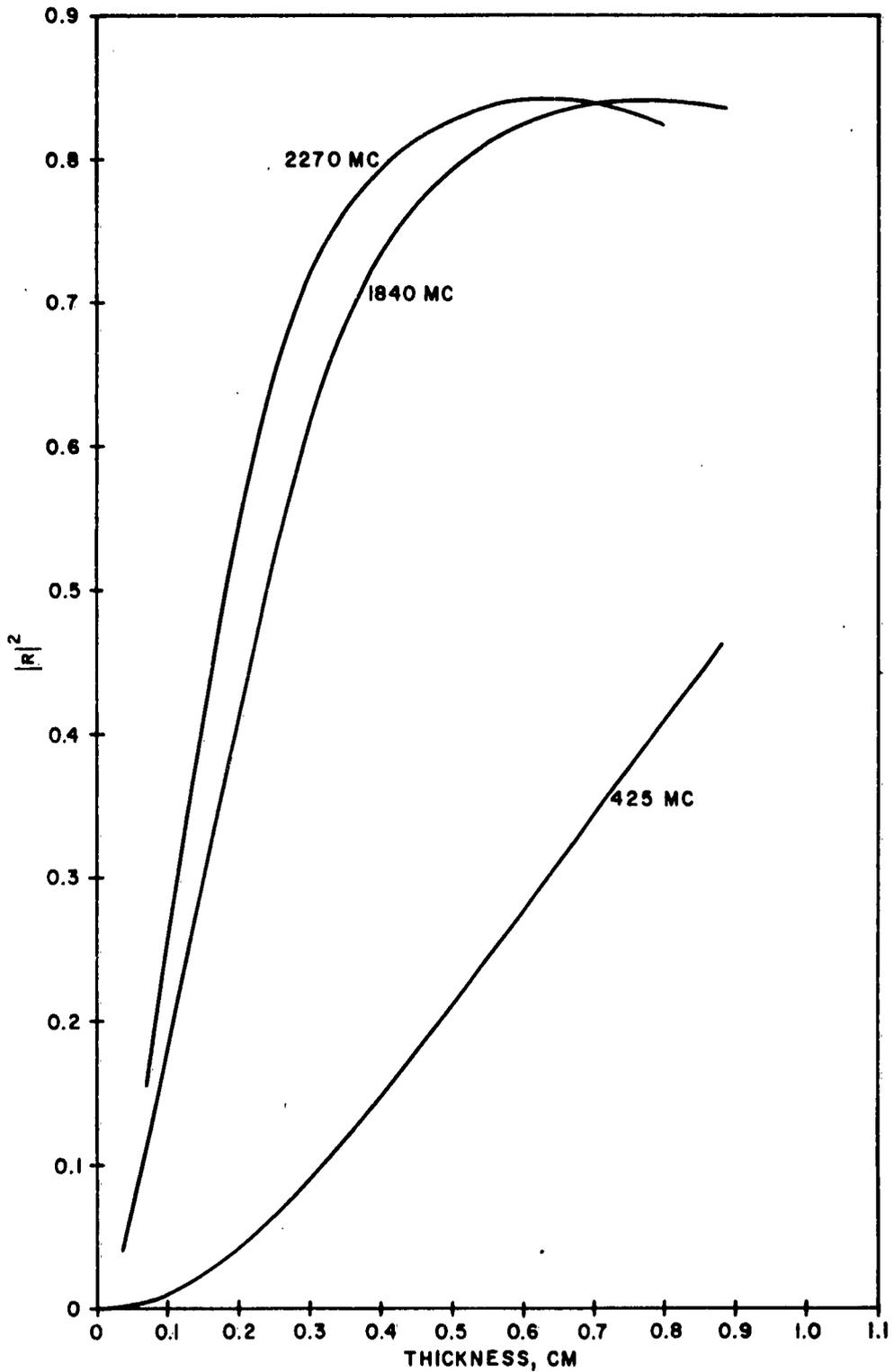
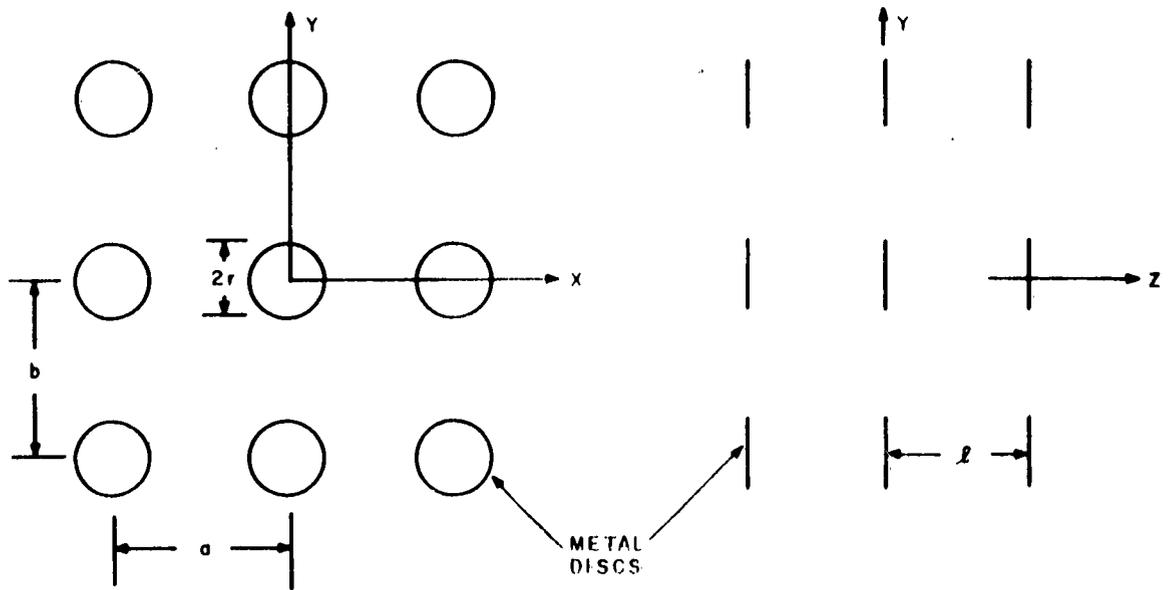
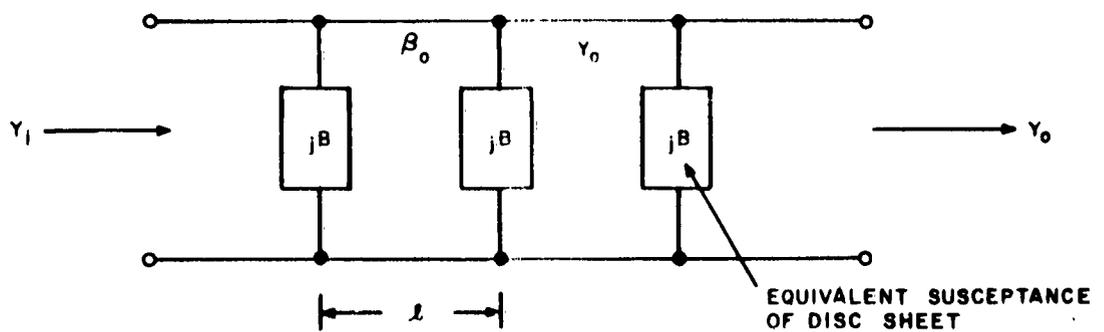


Figure 2-27. Reflection-Coefficient Magnitude vs. Slab Thickness for Dielectric Constant of 25



(A) THREE-DIMENSIONAL ARRAY OF METALLIC DISCS



(B) EQUIVALENT CIRCUIT OF THE ARRAY

Figure 2-28. Typical Artificial Dielectric Structure

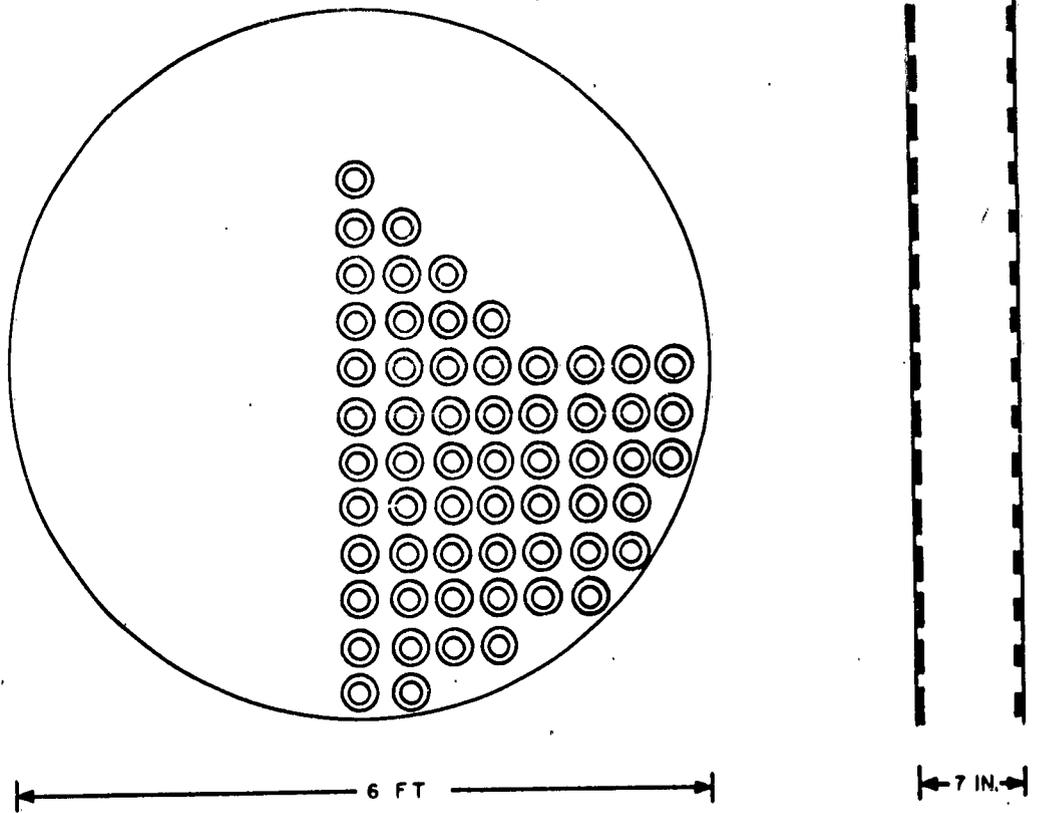


Figure 2-29. Basic Frequency-Selective Reflector

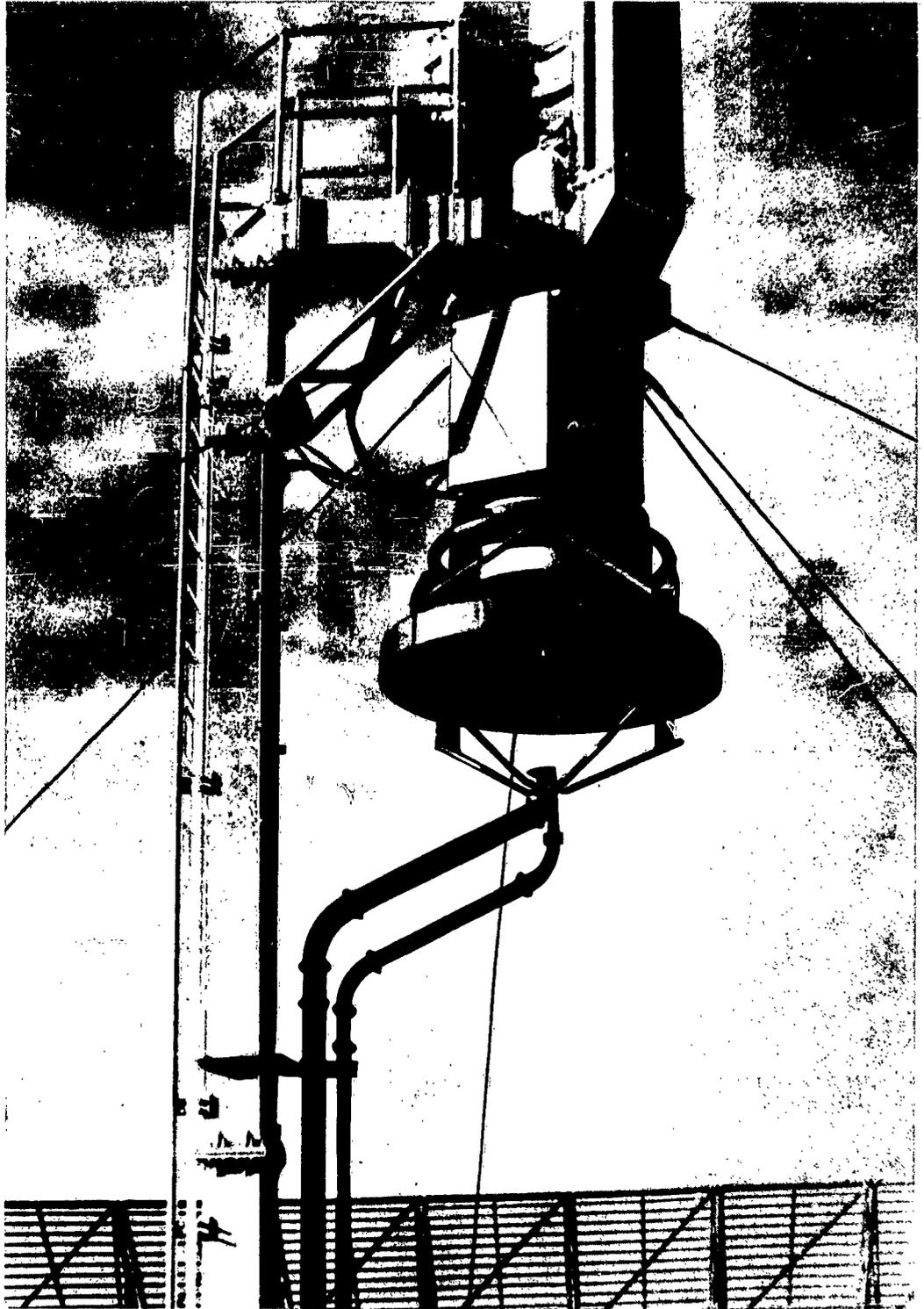


Figure 2-30. Trinidad Antenna Feed

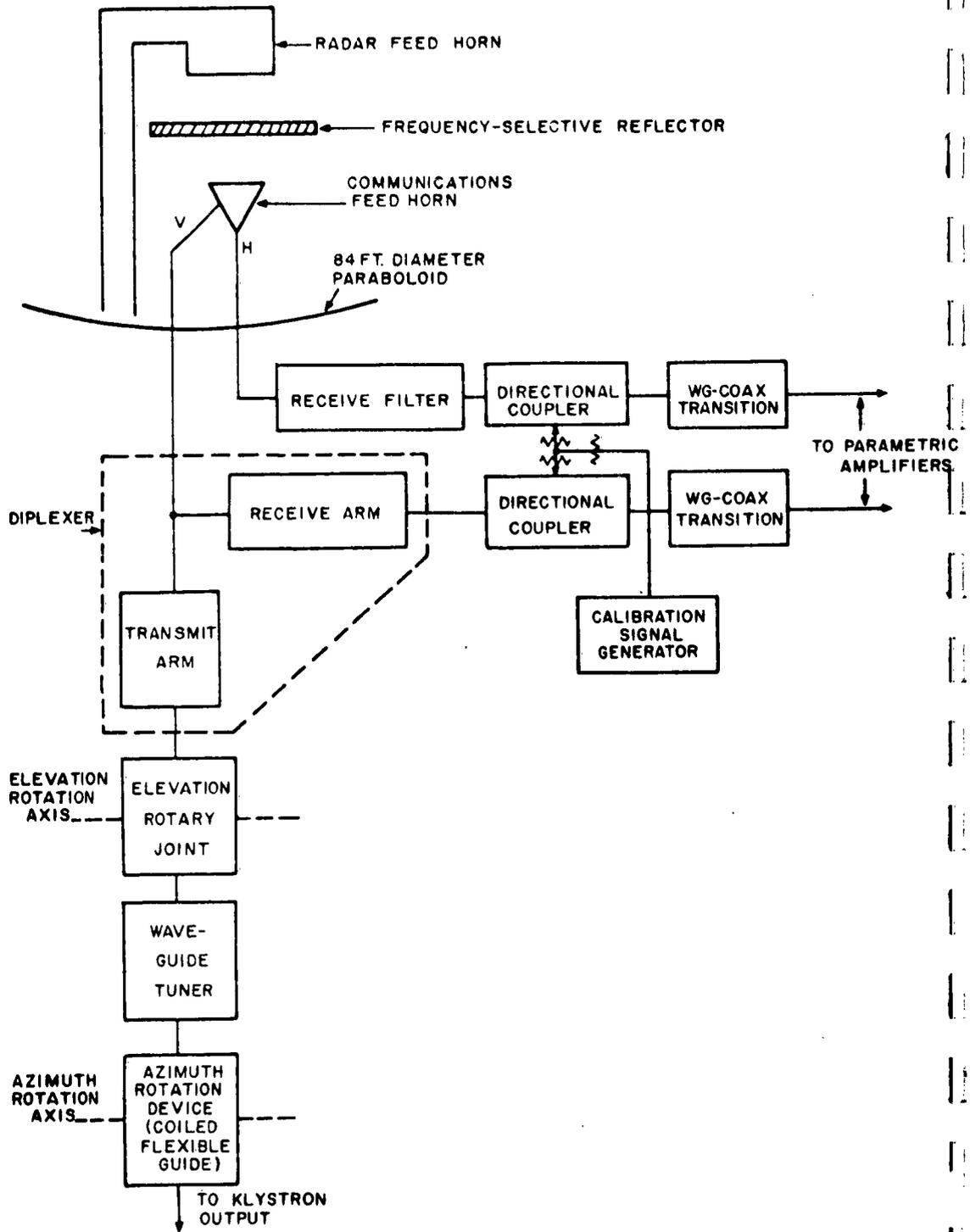


Figure 2-31. Trinidad Antenna Feed and Transmission System



Figure 2-32. Trindad Azimuth Waveguide Wrap-Up Assembly

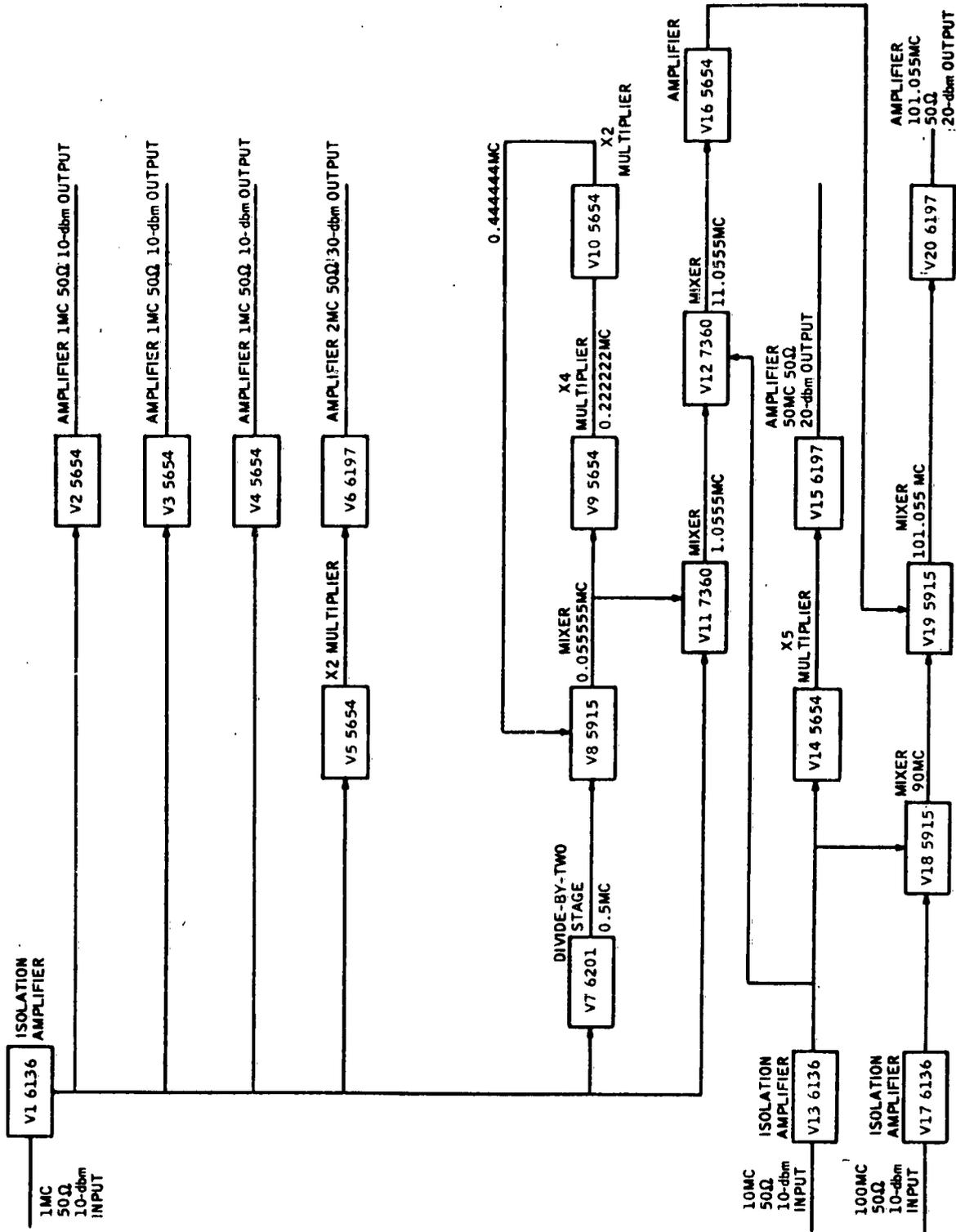


Figure 2-33. Page Frequency Synthesizer, Type T, Block Diagram

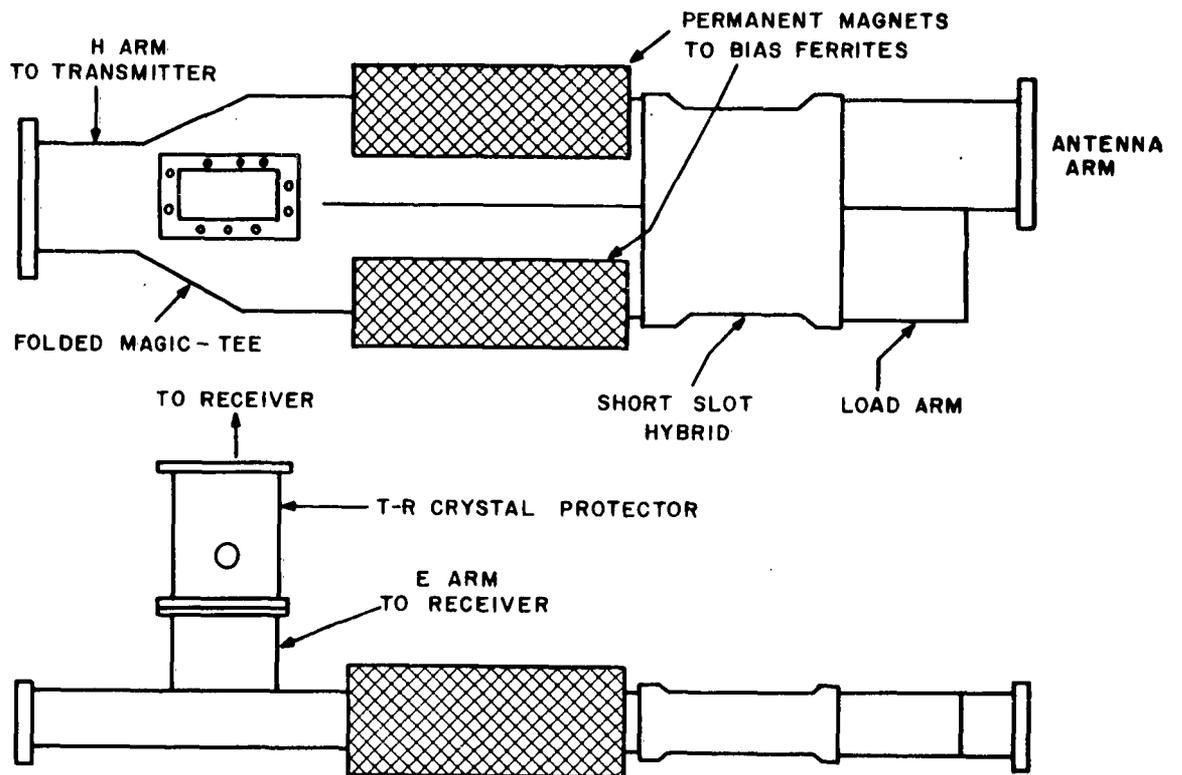
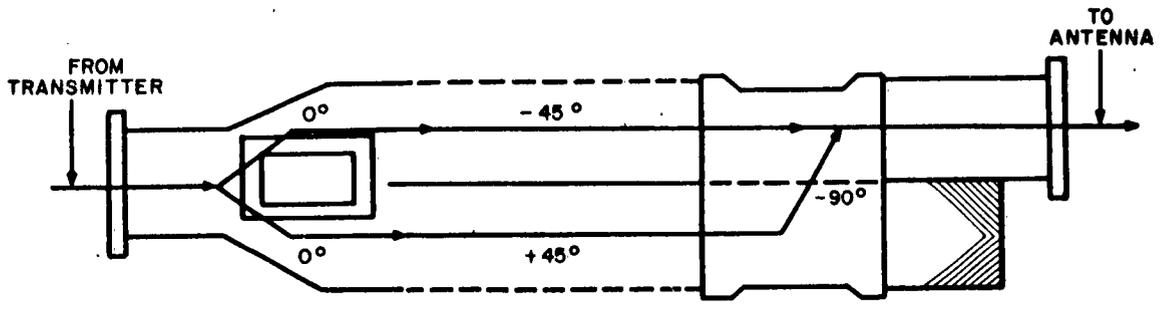
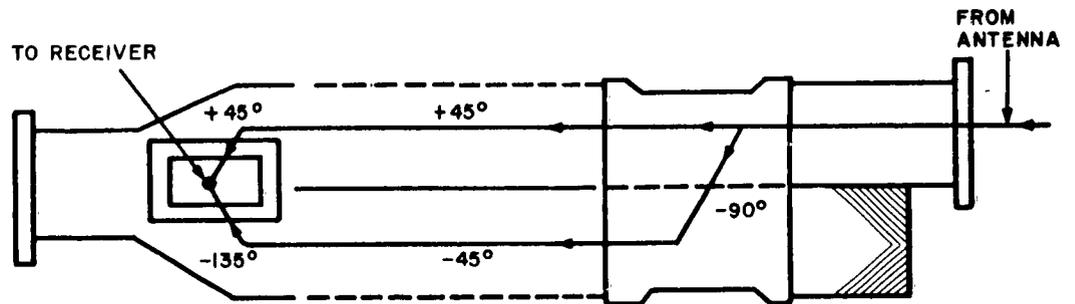


Figure 2-34. Trinidad Radar-Mode Duplexer



(A) TRANSMIT



(B) RECEIVE

Figure 2-35. Signal Paths Through Radar-Mode Duplexer

SECTION 3

RF SYSTEM PERFORMANCE MEASUREMENTS

3.1 GENERAL

The basic system parameters required to define system performance have been described in Paragraph 2.1. In-place equipment performance measurements required to establish these parameters are described in this section. These measurements are primarily in the areas of antenna performance (gain - patterns) and receiving-system sensitivity.

3.2 ANTENNAS

3.2.1 Floyd 2-gc Tracking Antenna

3.2.1.1 Gain. Gain of the Floyd Antenna was measured by direct comparison with a WR-430 standard-gain horn. The experimental arrangement is shown in Figure 3-1. Transmission was from a temporary boresight location approximately 0.6 mile from the tracking antenna. Received signals were compared on the Floyd station receiver, which had been calibrated over the range of received signal levels with the station standard signal generator. Accuracy of the direct gain measurement is estimated at + 1 db, and good agreement with gain deduced from the pattern beamwidths was obtained. The measured gain was 44.8 db.

3.2.1.2 Patterns. Using the instrumentation shown in Figure 3-1, antenna patterns were measured. The following plots are reproduced:

<u>Frequency</u>	<u>Polarization</u>	<u>Pattern</u>	<u>Figure number</u>
1.84 gc	horizontal	azimuth (E-plane)	3-2
1.84 gc	horizontal	elevation (H-plane)	3-3
2.27 gc	horizontal	azimuth (E-plane)	3-4
2.27 gc	horizontal	elevation (H-plane)	3-5
2.27 gc	vertical	elevation (E-plane)	3-6

The 1.84-gc patterns are sum patterns, taken at the transmitter port. The 2.27-gc patterns are for power divider settings in the range of 0.5-db crossover, and are taken at the receiver ports. The following characteristics can be summarized:

	<u>1.84-gc</u>	<u>2.27-gc</u>
E-plane beamwidth	1° 04'	1°10' - 1°18'
H-plane beamwidth	1° 02'	0° 55'
E-plane sidelobe suppression	18-21 db	15-22 db
H-plane sidelobe suppression	15-20 db	10-19 db
Crossover level	-	0.4-0.6 db

It is believed that the single high sidelobe (-10 db, observed in the elevation pattern at 2.27-gc) is attributable to the use of an interim foresight location with a nonideal foreground.

3.2.1.3 VSWR. Each port of the Floyd 2-gc feed is equipped with a three-stub tuner capable of matching the feed vswr (nominal 1.5 maximum) at any frequency in the 1.7-2.4 gc range. Nevertheless, the adjustment of vswr on the receive ports involves more than a simple match at one point. This is because the small residual vswr of the rotary phase shifter adds in different phase as the shifter is rotated, causing the vswr as seen by the receiver to vary at the scan rate.

If the variations are large they will affect the gain of the parametric amplifiers, introducing a spurious scan-frequency modulation on the received carrier and confusing the tracking function. For optimum performance the maximum vswr must be held below 1.4.

Adjustment consists of simultaneous tuning of the phase-shifter trimmer and the receive-port tuner, for minimum vswr variation at the receive port. This is best performed by observing a reflectometer output on the vertical plates of an oscilloscope, while the sweep is synchronized to the phase-shifter motor. It can, however, be accomplished by making point-by-point measurements as the phase shifter is turned by hand.

The receive port vswr versus phase-shifter position (measured as shown in Figure 3-7) is shown in the two plots of Figure 3-8.

3.2.2 Trinidad 2-gc Feed

3.2.2.1 Compatibility Test. Since the 2-gc communication feed at Trinidad is permanently mounted in the same aperture with the 425-mc feed of the AN/FPT-5 radar, a feasibility test¹⁹ to demonstrate non-interference with the radar performance was required. These measurements, conducted with the aid of G. E. radar operation personnel, consisted of measurements of the effect of the 2-gc feed on the vswr, pattern, boresight error, and sensitivity of the Trinidad radar as follows:

a. VSWR. The untuned vswr of the 425-mc feed was found to be 1.29 with the 2-gc feed and subreflector in place, compared with 1.25 before installation.

b. Pattern. No discernable effect was noted on the 425-mc patterns as a result of the addition of the 2-gc feed. Typical 425-mc patterns after the 2-gc feed installation are shown in Figure 3-9.

c. Boresight. No discernable boresight shift could be attributed to the 2-gc installation.

d. Sensitivity. Tracking of objects of known cross section before and after the 2-gc installation disclosed no discernable reduction in system sensitivity.

3.2.2.2 Gain. Gain of the Trinidad Antenna was also measured by direct comparison with a WR-430 standard-gain horn, and was verified by pattern measurements. The experimental arrangement is shown in Figure 3-10. The boresight transmitter was collocated with the 425-mc boresight on Mt. Catherine for these measurements. The calibrated attenuator of the signal generator was used for the gain comparison, by adjusting for equal received-signal levels. Accuracy is estimated at ± 1 db. The gain measured, 52.0 db, corresponds closely to that which can be computed from the pattern beamwidths.

3.2.2.3 Patterns. Using the same arrangement as shown in Figure 3-10, antenna patterns were measured. The following patterns are presented here:

<u>Frequency</u>	<u>Polarization</u>	<u>Pattern</u>	<u>Figure number</u>
1.84 gc	horizontal	azimuth (E-plane)	3-11 (a)
1.84 gc	horizontal	elevation (H-plane)	3-11 (b)
2.27 gc	vertical	azimuth (H-plane)	3-12 (a)
2.27 gc	vertical	elevation (E-plane)	3-12 (b)

Beamwidths and sidelobe levels are tabulated below:

	<u>Beamwidth</u>	<u>Max. Sidelobe level</u>
1.84 gc E-plane	33'	-18 db
1.84 gc H-plane	29'	-11 db
2.27 gc E-plane	26'	-11 db
2.27 gc H-plane	27'	-21 db

3.3 RECEIVING SYSTEM SENSITIVITY

3.3.1 Parametric Amplifier Performance

The parametric amplifier noise figures were measured using an AIL model 70 hot-cold body noise generator. For noise figures in the 1-2 db range, this technique, utilizing a 78°K liquid-nitrogen reference, yields very accurate results, estimated in the order of ± 0.1 db. The test arrangement is shown in Figure 3-13 (a), and the results are tabulated below. These figures include circulator losses and second-stage contribution.

<u>Parametric Amplifier</u>	<u>Noise figure (db)</u>	<u>Noise temp (°K)</u>
Floyd ch. 1 (vert.)	1.6	130
Floyd ch. 2 (horiz.)	1.5	120
Trinidad ch. 1 (horiz.)	1.3	100
Trinidad ch. 2 (vert.)	1.7	140

3.3.2 Antenna Temperature

The total effective antenna temperature includes effects of ground spillover noise, atmospheric attenuation, cosmic noise, and line and filter losses. This antenna temperature was measured using the arrangement shown in Figure 3-13 (b). First the cold body was connected to the receiver input through a coaxial line of known attenuation, and the amplified IF noise power P_1 was measured. This power is given by:

$$P_1 = KB [T_R + LT_1 + (1-L)T_N], \quad (12)$$

where

K = Boltzman's constant,

B = IF bandwidth,

T_r = receiver temperature,

L = fraction power loss of line

T_l = line temperature = $T_o = 290^\circ\text{K}$, and

T_n = liquid nitrogen temperature = 78°K

The antenna was then connected to the receiver input (through its normal transmission system so that line losses would be included in the antenna temperature measured), and the resulting IF power P_2 was measured. Here the measured power is given by:

$$P_2 = KB (T_r + T_a), \quad (13)$$

where T_a = antenna temperature as seen by receiver.

Dividing Equation (13) by Equation (12) gives

$$\frac{P_2}{P_1} = \frac{T_a + T_r}{T_r + LT_l + (1-L)T_n}, \quad (14)$$

or expressed logarithmically,

$$P_2 \text{ (db)} - P_1 \text{ (db)} = \log \left[\frac{T_a + T_r}{T_r + LT_l + (1-L)T_n} \right] \quad (15)$$

Hence, the antenna temperature T_a is given by

$$T_a = [T_r + LT_l + (1-L)T_n] \log^{-1} [P_2 \text{ (db)} - P_1 \text{ (db)}] - T_r. \quad (16)$$

Since T_r , L, T_l and T_n are all known quantities, T_a is computed as above from the measured difference of P_2 and P_1 . The accuracy of this technique is estimated at $\pm 10^\circ\text{K}$.

The total antenna temperature, as seen by the receiver, was measured as a function of antenna elevation angle. For elevations greater than about 5 degrees, the antenna temperature is observed to be relatively constant. The total antenna temperature is plotted versus antenna elevation in Figure 3-14 for the Floyd installation (2.27 gc).

3.3.3 System Temperature

The system temperature is simply the sum of the total antenna temperature (as seen at the receiver terminal) and the total receiver temperature. For antenna elevation angles greater than 5 degrees, the receiving system temperatures are tabulated below:

<u>Receiving System</u>	<u>System Temperature (°K)</u>
Floyd (vertical polarization)	260
Floyd (horizontal polarization)	275

3.4 DUPLEXING FILTERS

The vswr and insertion loss of the Floyd and Trinidad duplexing filters are plotted in Figures 3-15 and 3-16, respectively. Passband insertion loss varies between 0.15 and 0.4 db, while passband vswr remains below 1.1 in all cases. Rejection of the receive filters at transmit frequencies exceeded the capability of the measuring equipment (90-95 db), while attenuation of the transmit filters at the receive frequency was over 80 db. This level of performance is satisfactory for the proper functioning of the duplexing system.

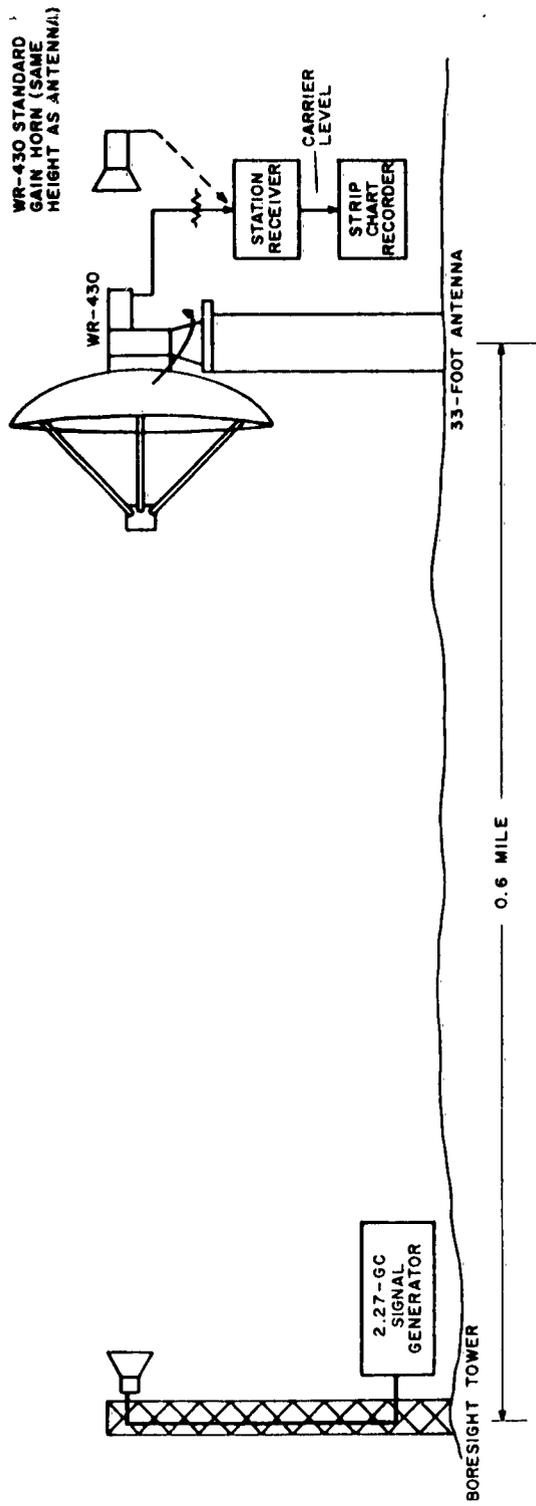


Figure 3-1. Floyd Antenna-Gain and Radiation-Pattern Instrumentation

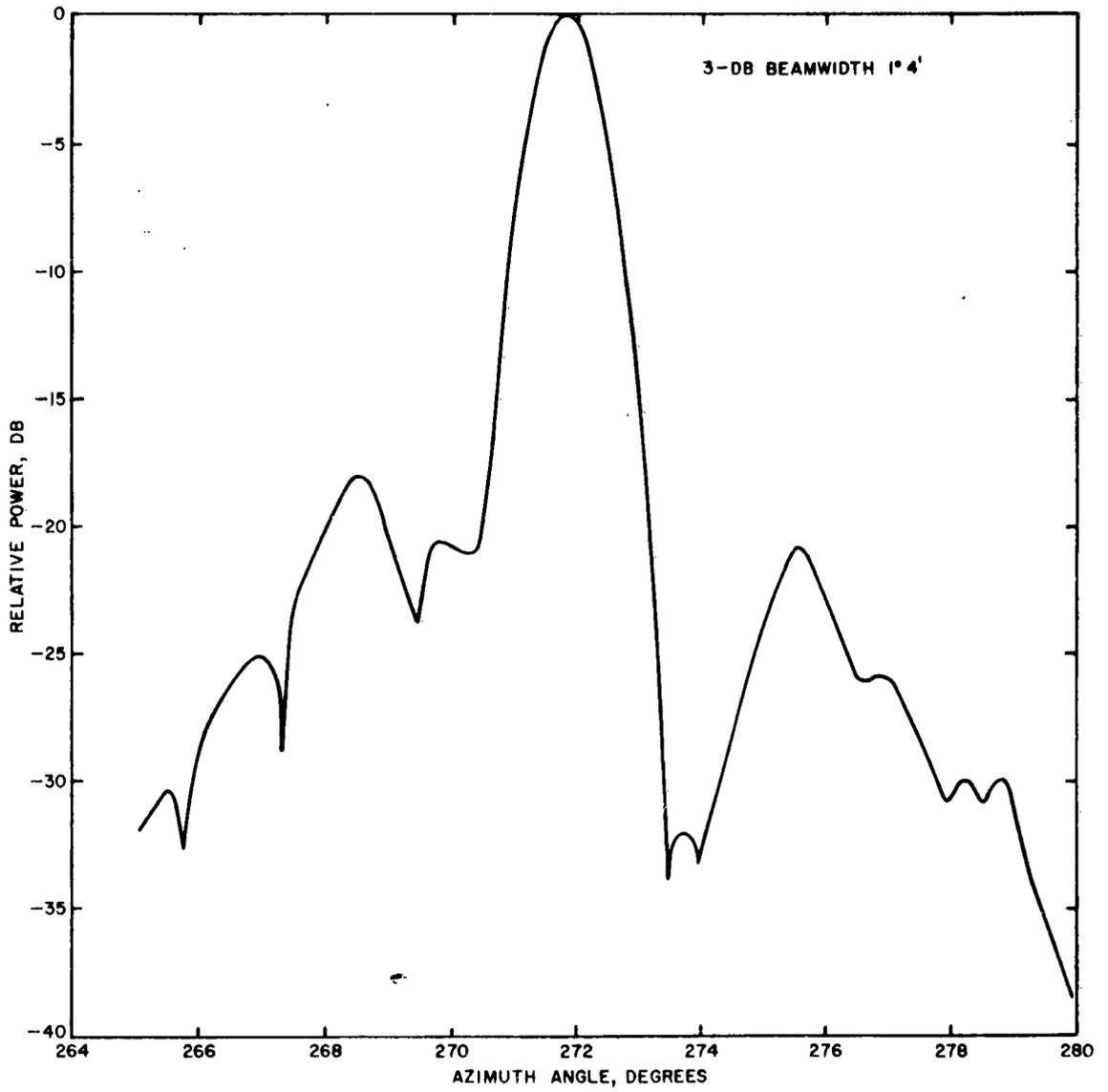


Figure 3-2. Floyd Antenna Azimuth Pattern (E Plane),
Horizontal Polarization, 1.87 GC

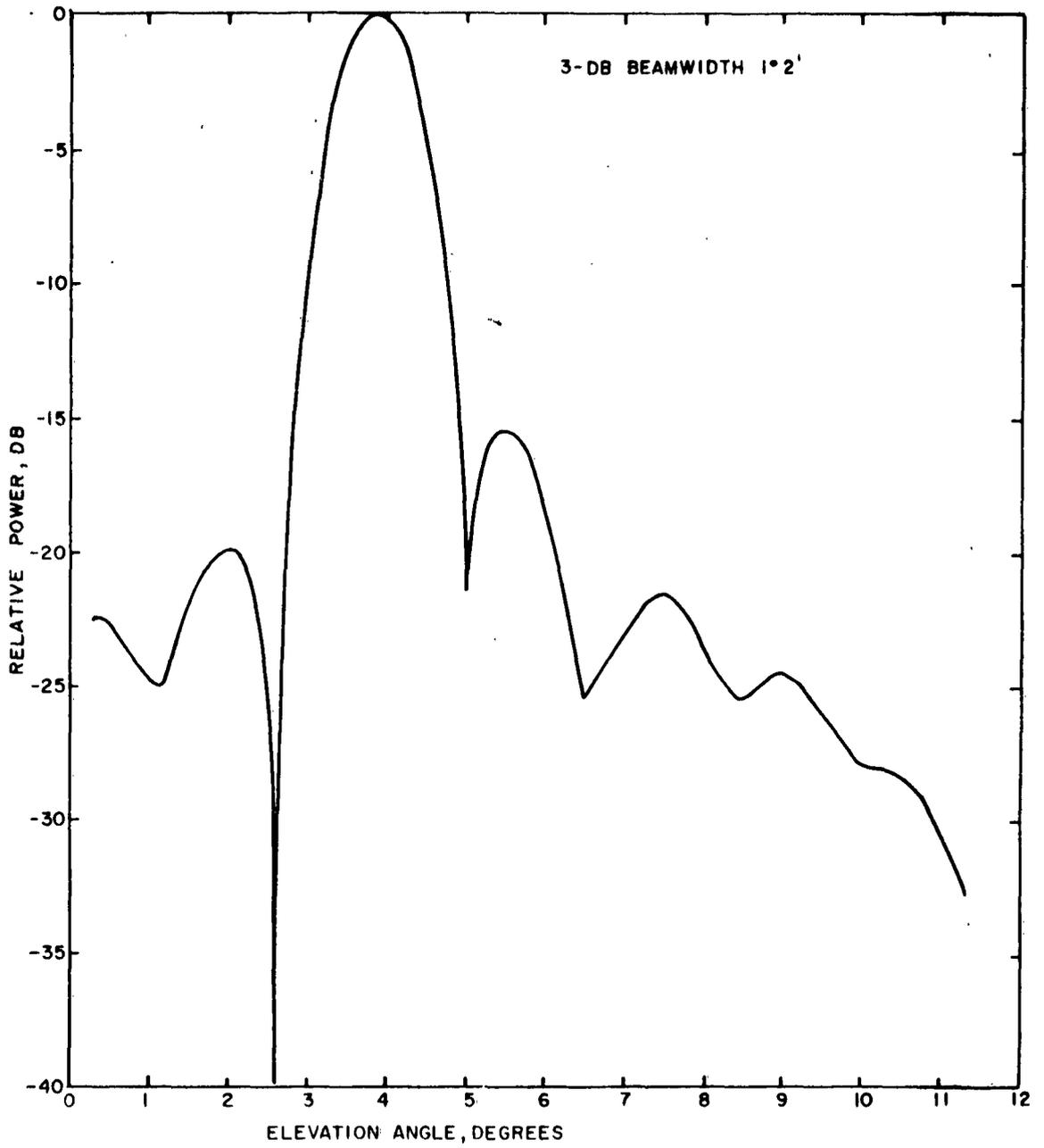


Figure 3-3. Floyd Antenna Elevation Pattern (H Plane),
Horizontal Polarization, 1.87 GC

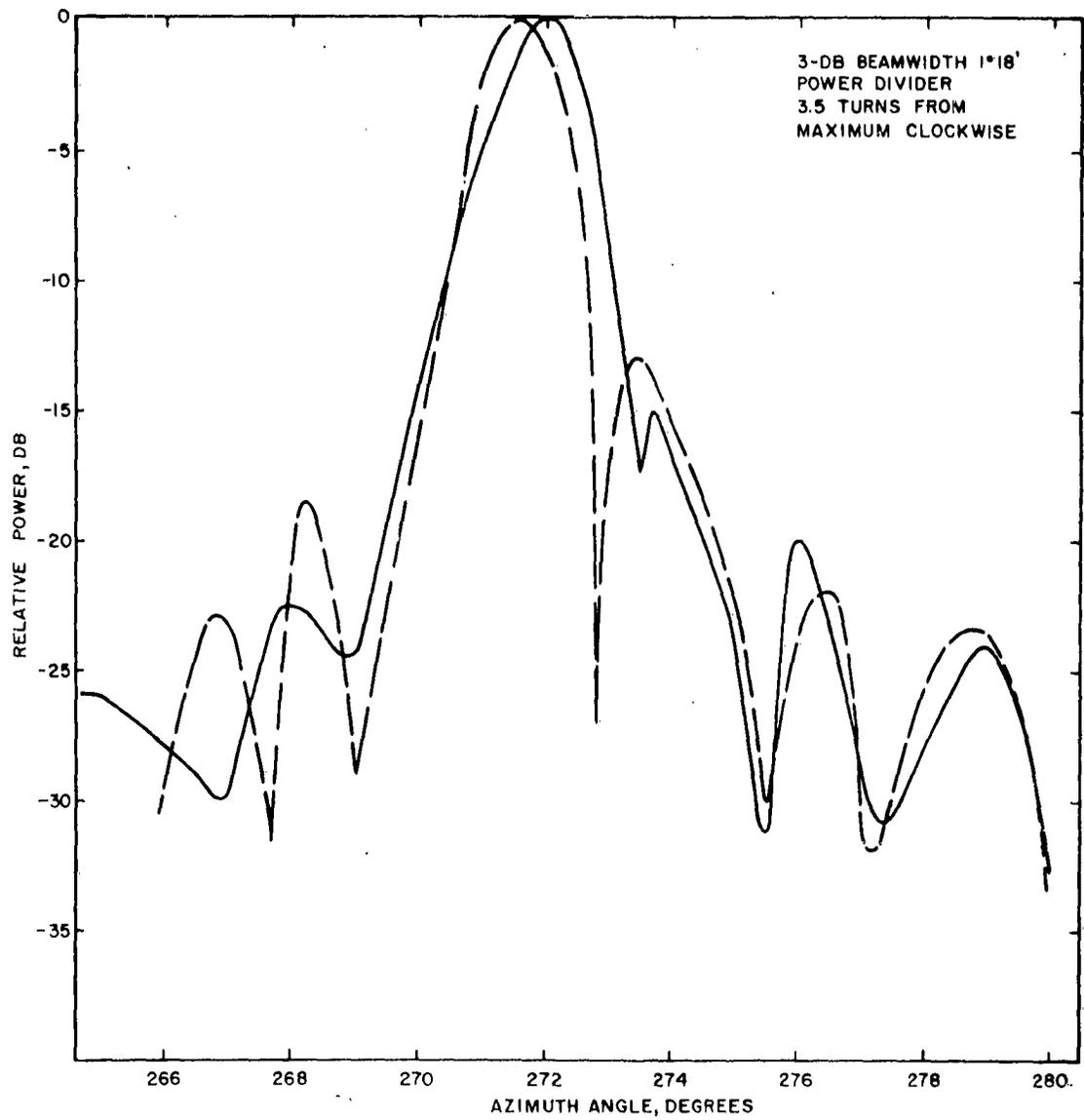


Figure 3-4. Floyd Antenna Azimuth Pattern (E Plane),
Horizontal Polarization, 2.27 GC

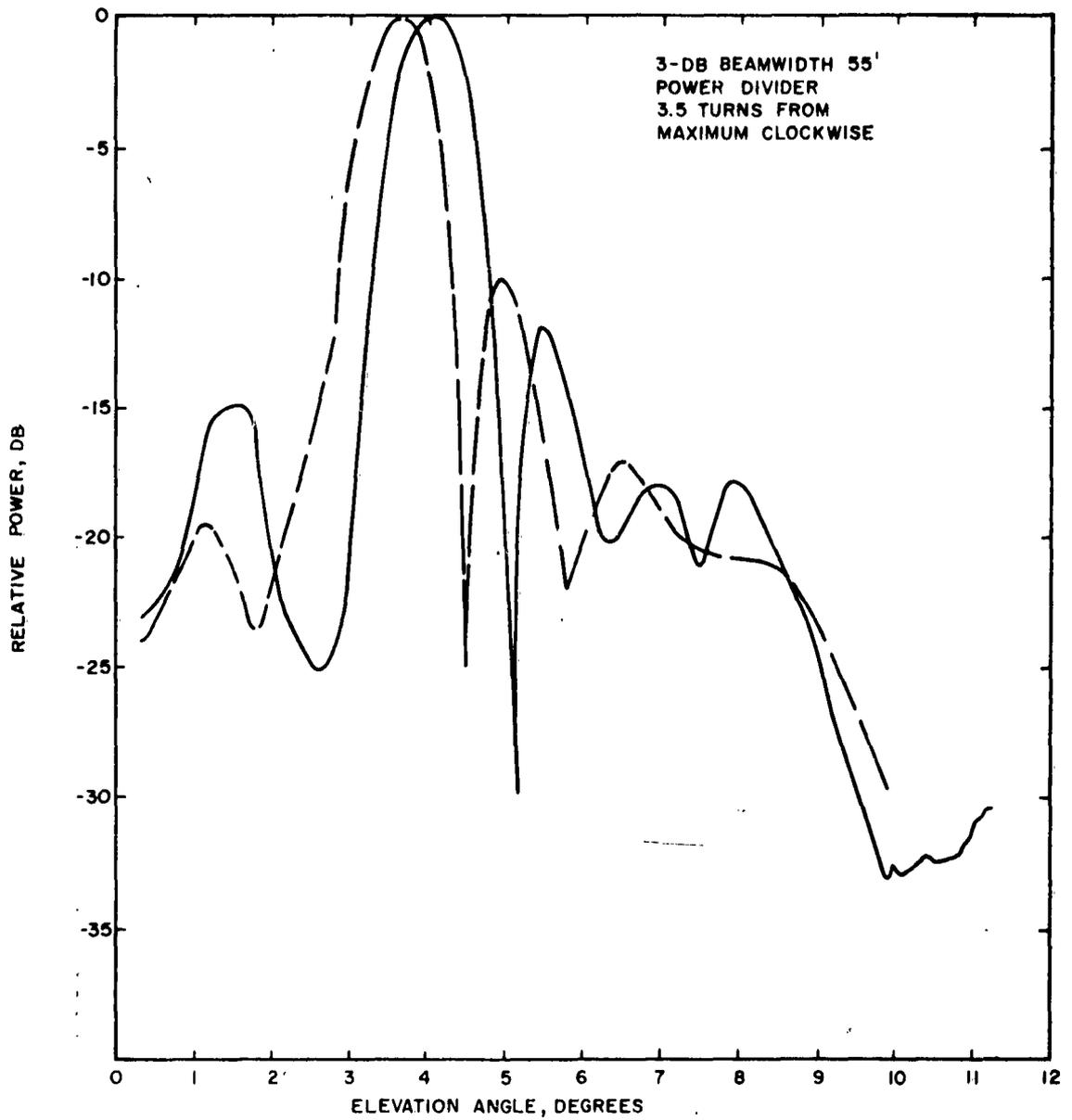


Figure 3-5. Floyd Antenna Elevation Pattern (H Plane),
Horizontal Polarization, 2.27 GC

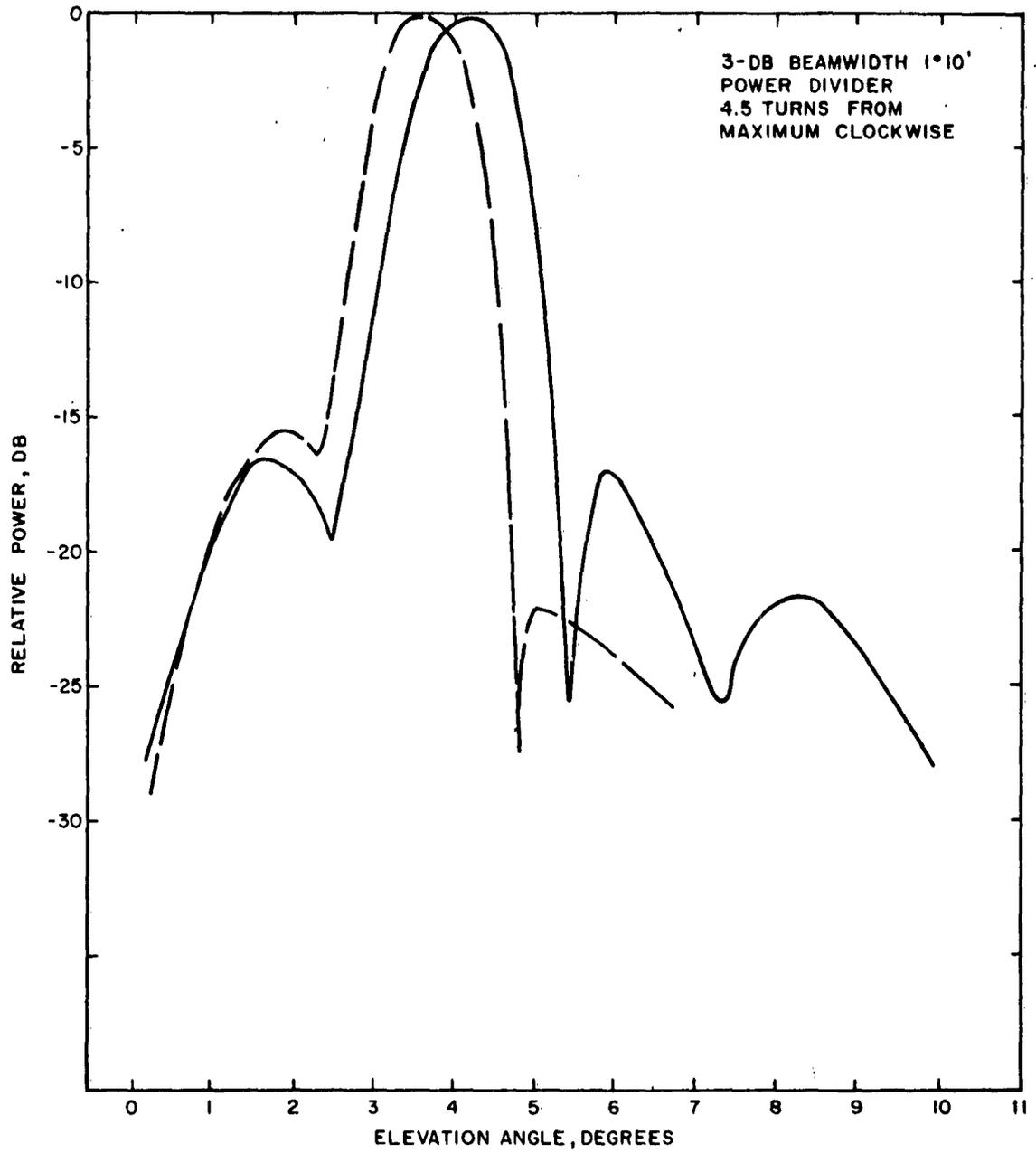


Figure 3-6. Floyd Antenna Elevation Pattern (E Plane),
Vertical Polarization, 2.27 GC

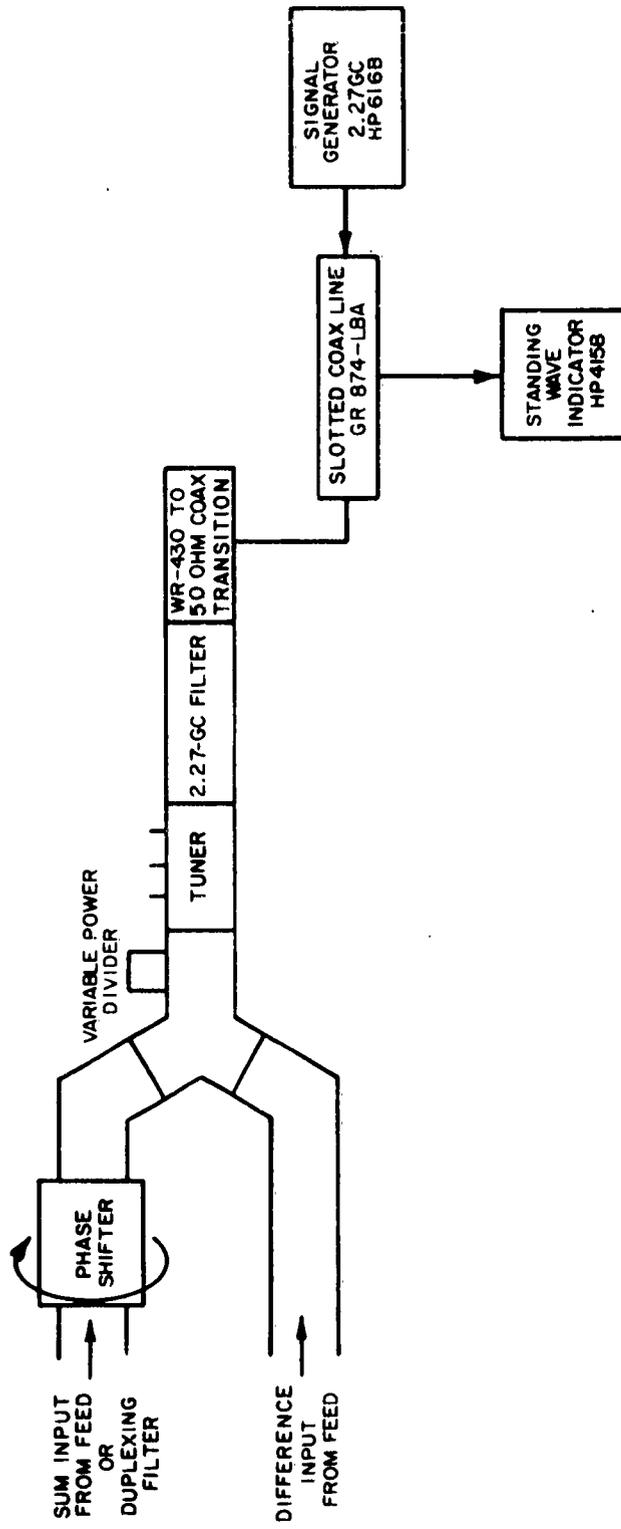


Figure 3-7. Floyd VSWR Instrumentation

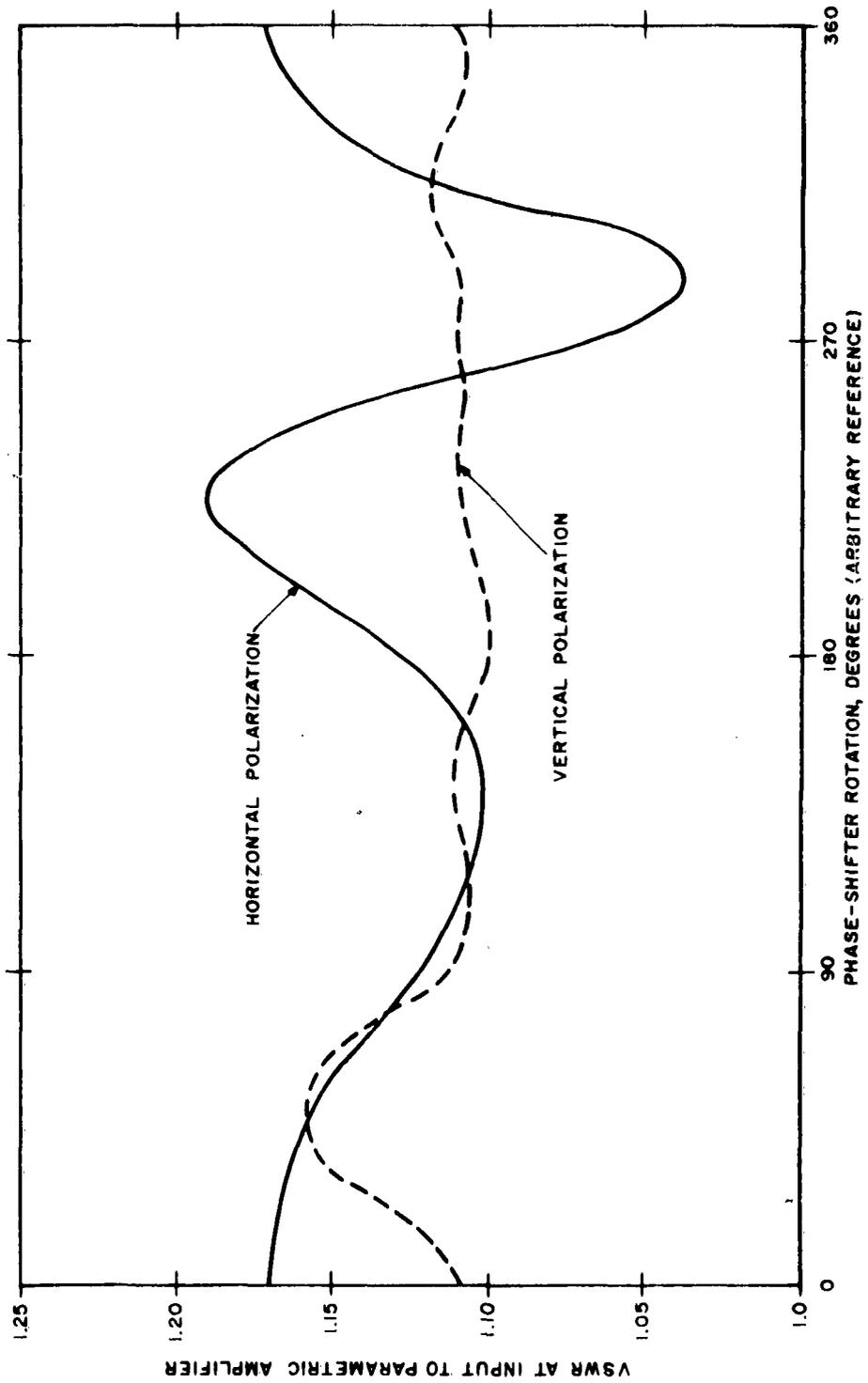
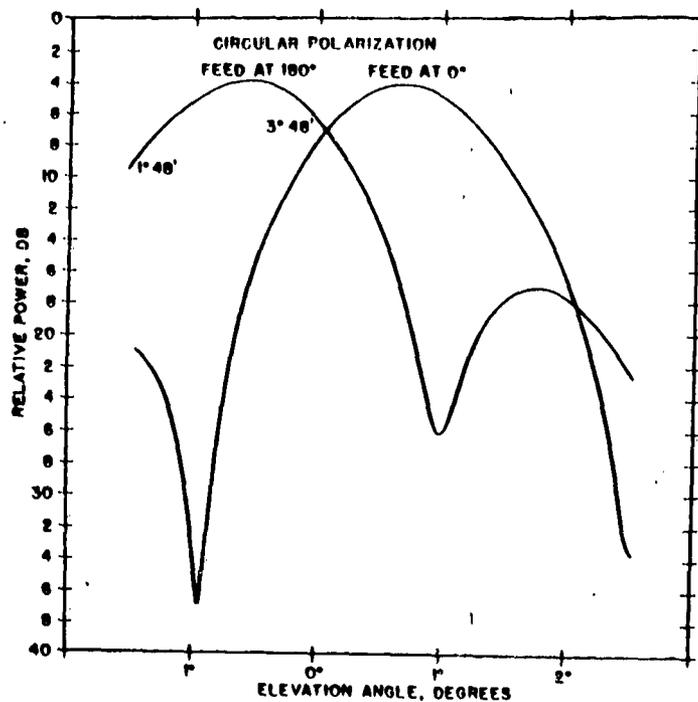
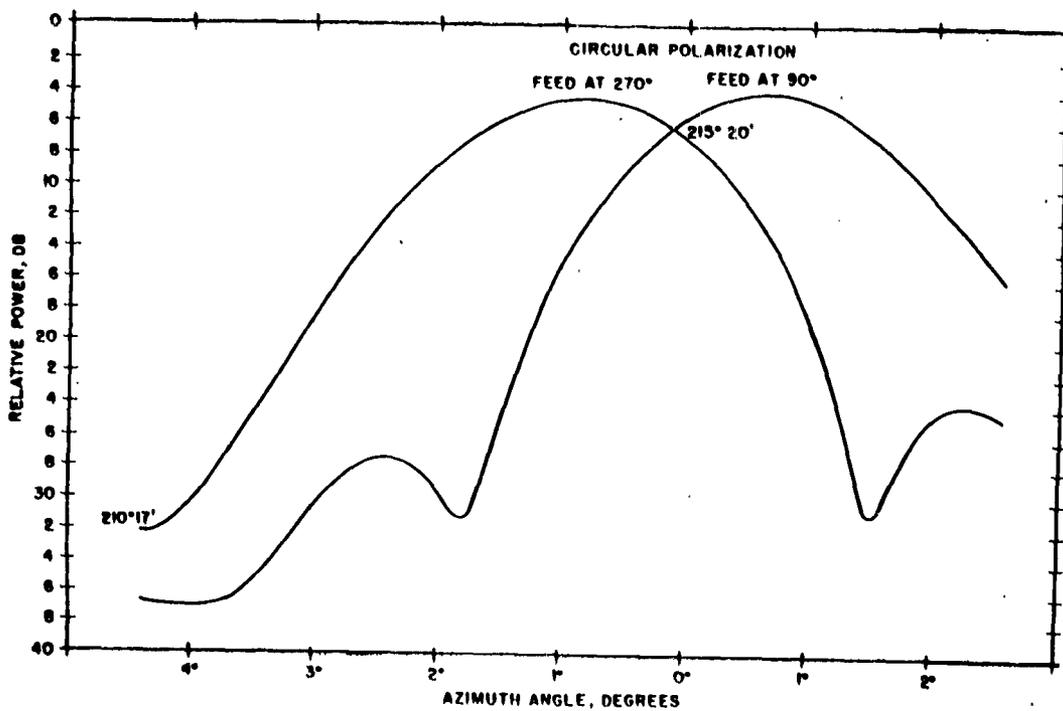


Figure 3-8. Floyd Antenna VSWR vs. Phase Shifter Position



(A) ELEVATION PATTERN AT 215° 20' AZIMUTH ANGLE



(B) AZIMUTH PATTERN AT 3° 48' ELEVATION

Figure 3-9. Typical 425-MC Crossover Pattern of Trinidad Tracking Antenna After 2-GC Feed Installation

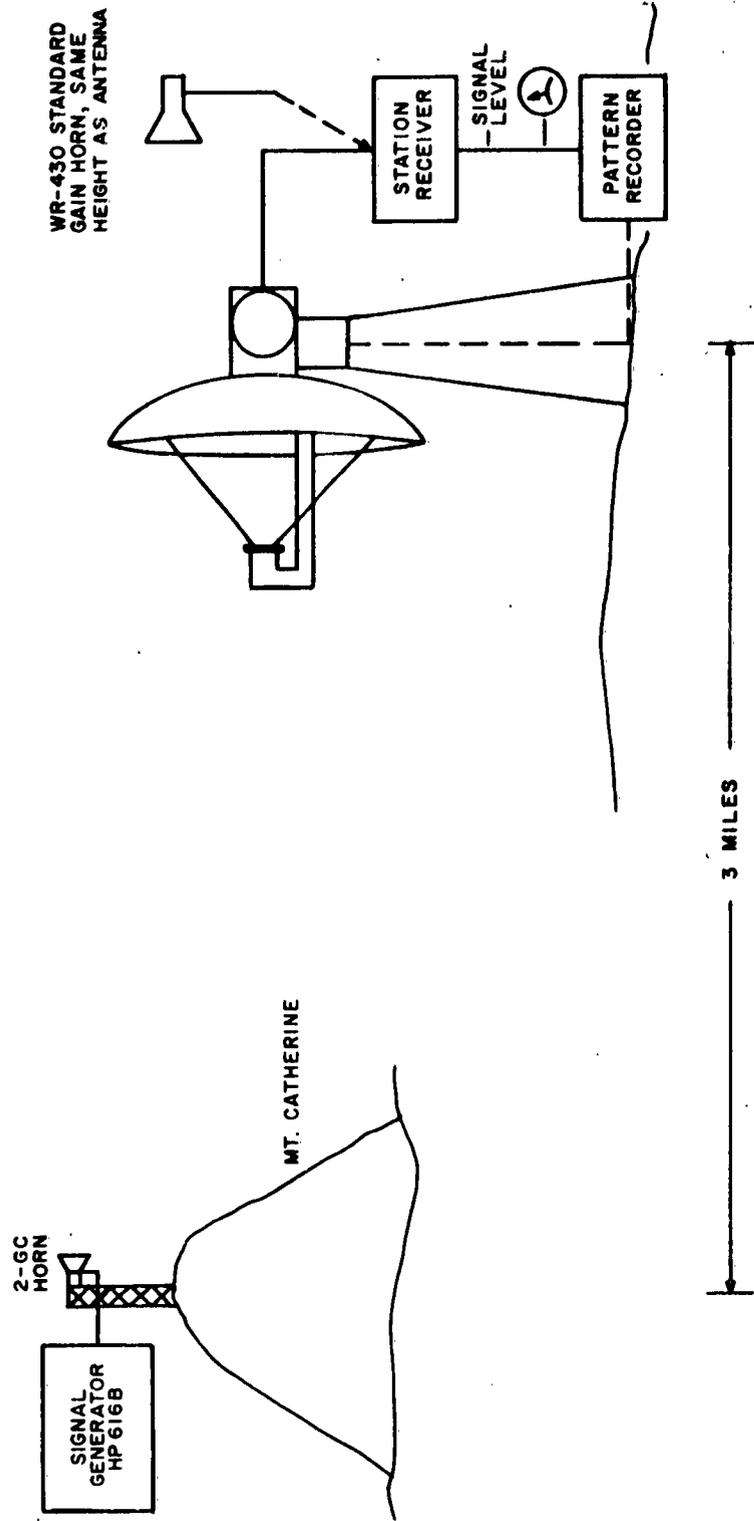
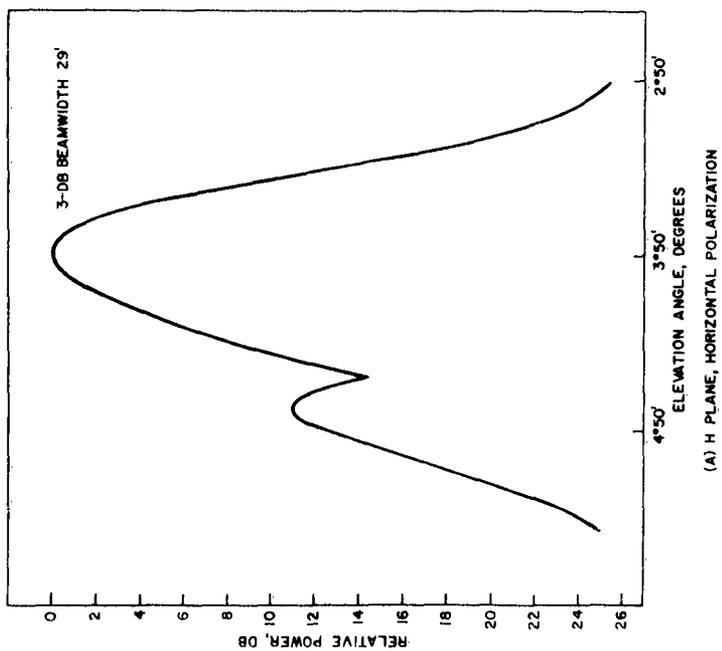
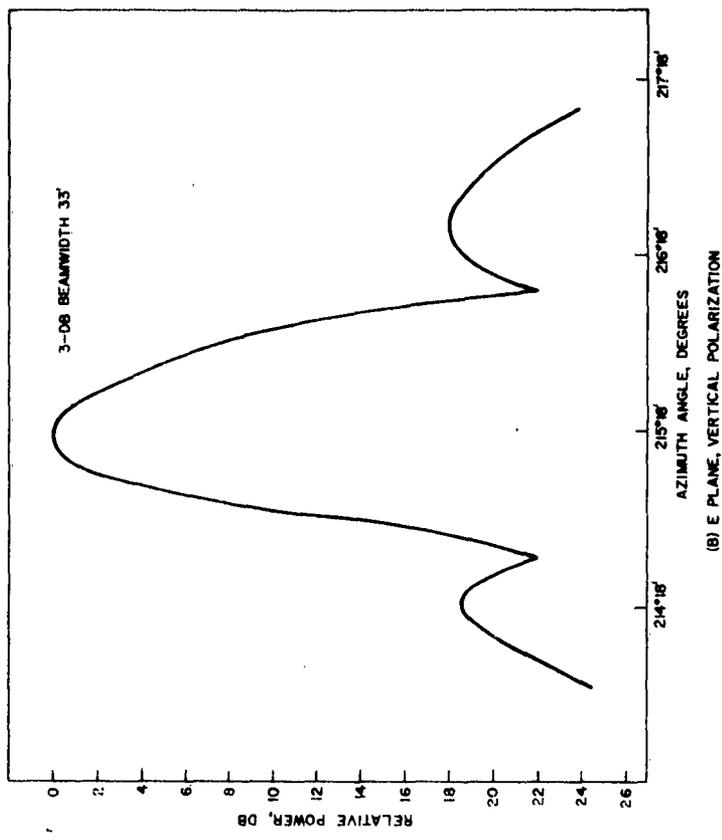


Figure 3-10. Trinidad Antenna-Gain, and Radiation-Pattern Instrumentation



(A) H PLANE, HORIZONTAL POLARIZATION



(B) E PLANE, VERTICAL POLARIZATION

Figure 3-11. Trinidad Antenna Radiation Patterns, 1.87 GC

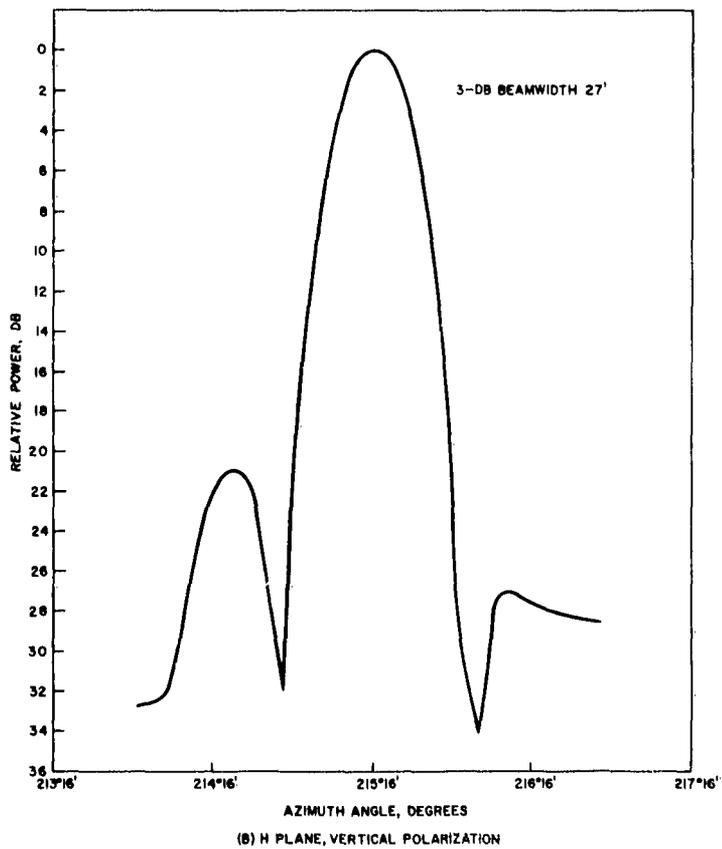
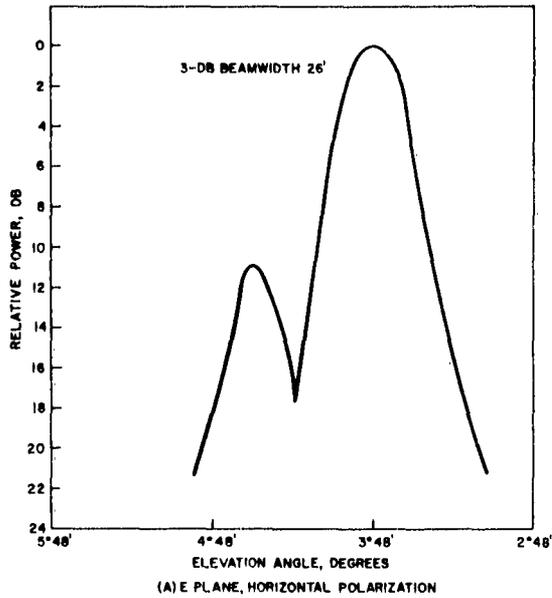
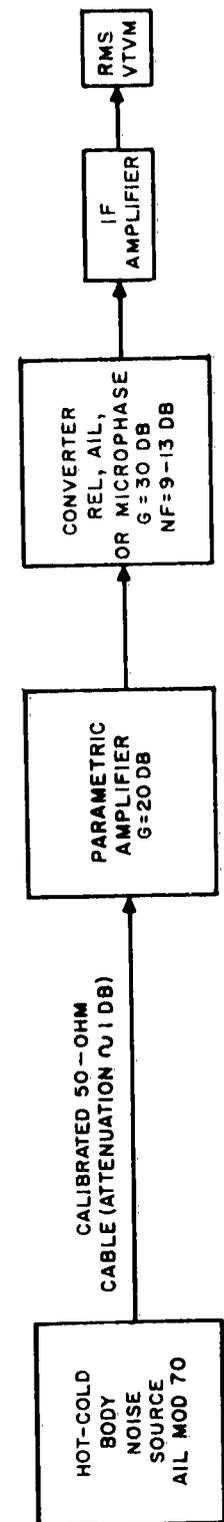
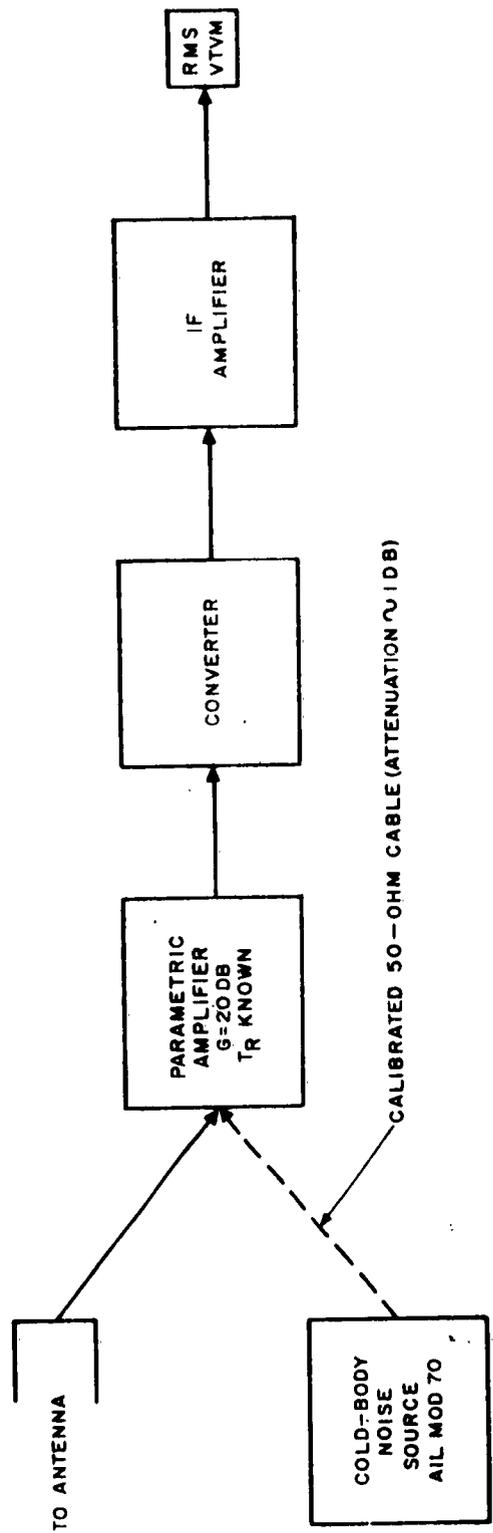


Figure 3-12. Trinidad Antenna Radiation Patterns, 2. 27 GC



(A) RECEIVER NOISE - FIGURE MEASUREMENT



(B) ANTENNA TEMPERATURE MEASUREMENT

Figure 3-13. Receiving System Sensitivity Instrumentation

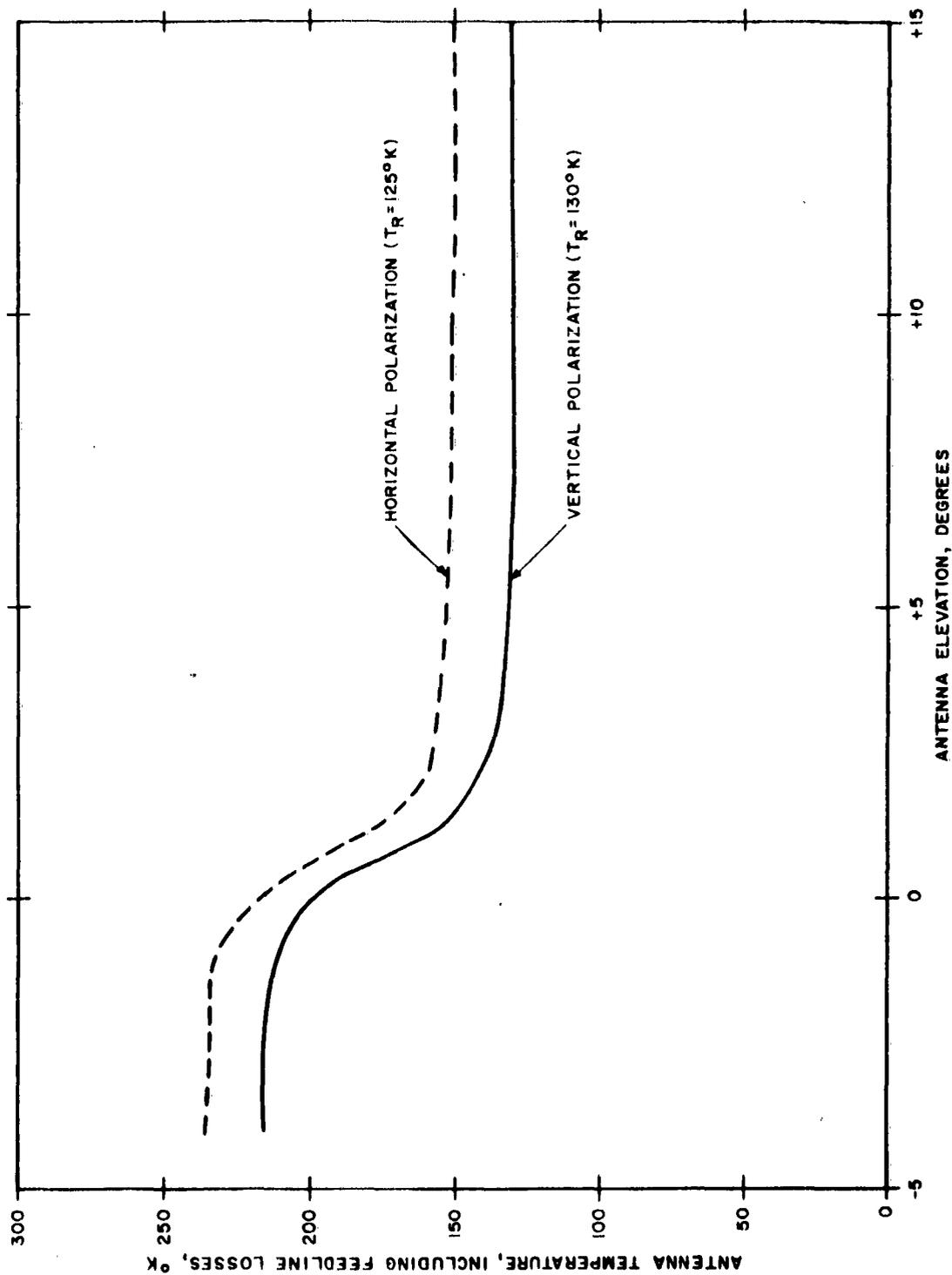
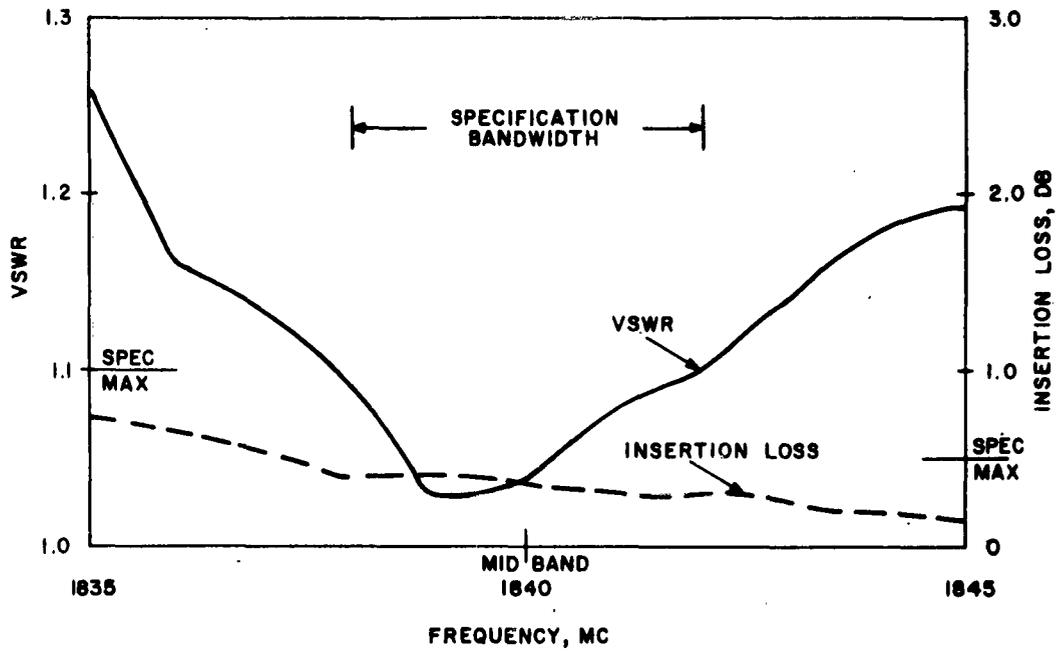
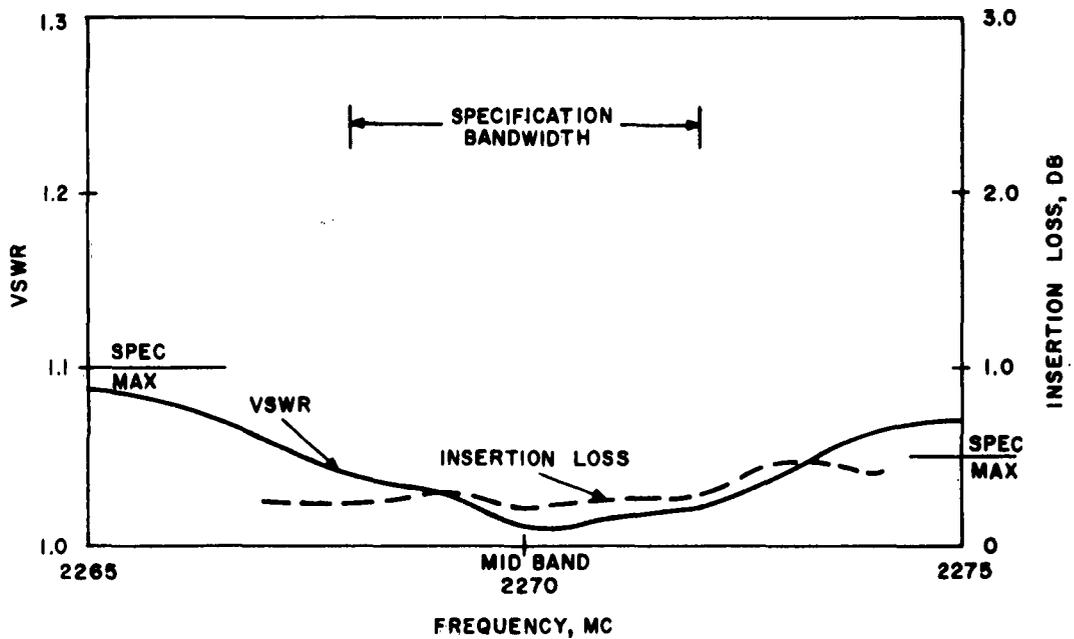


Figure 3-14. Floyd Antenna Temperature vs. Elevation Angle

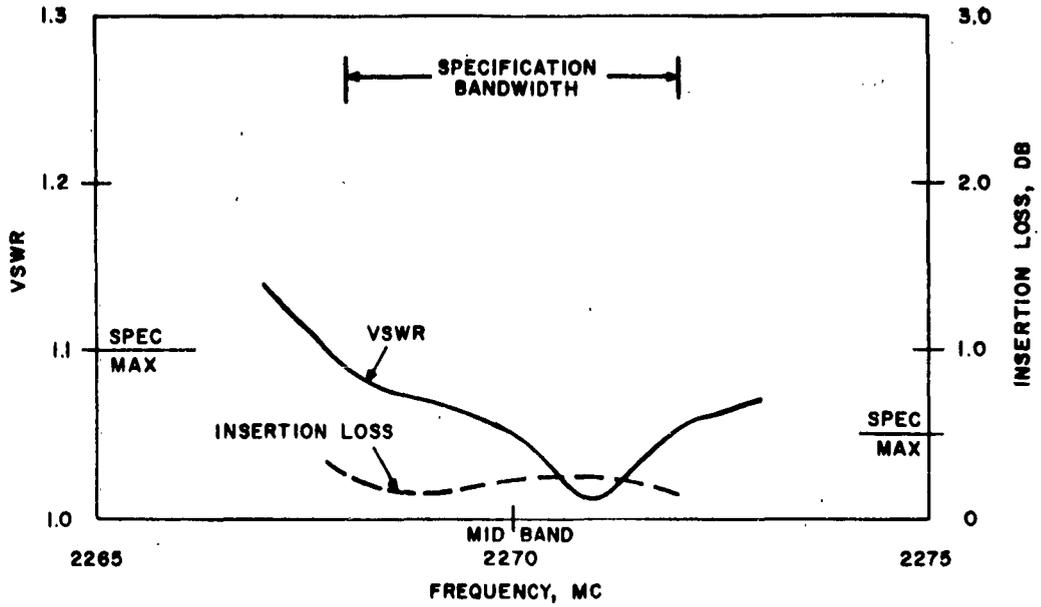


(A) REJECTION AT 2270 MC > 90DB - TRANSMIT ARM

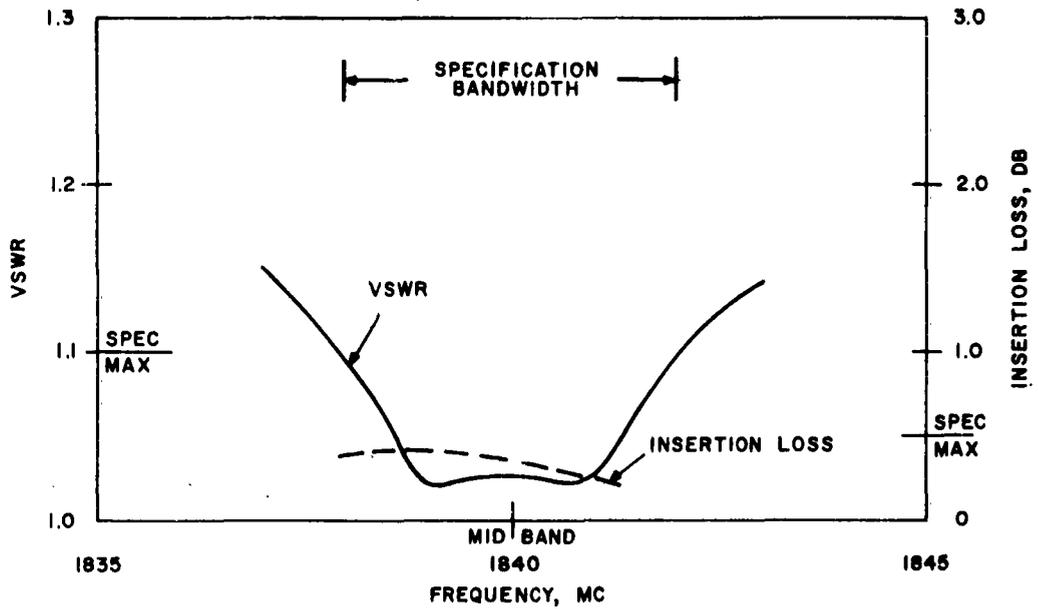


(B) REJECTION AT 1840 MC > 87DB - RECEIVE ARM

Figure 3-15. Passband Characteristics of Floyd Duplexing Filter



(A) REJECTION AT 1840MC > 83 DB - TRANSMIT ARM



(B) REJECTION AT 2270MC > 95 DB - RECEIVE ARM

Figure 3-16. Passband Characteristics of Trinidad Duplexing Filter

SECTION 4
TRACKING SYSTEM PERFORMANCE MEASUREMENTS

4.1 INTRODUCTION

In addition to performance measurements on the equipment at the Floyd and Trinidad sites, a number of performance measurements were made on the systems. These measurements were limited by degradation in the Echo I satellite that had occurred by the time the present system was made operational and by delays in the launching of the Echo II satellite. The reflected signal obtained from the presently degraded Echo I satellite had fallen below the -127 dbm threshold of the Floyd Radar Tracking Facility for most positions, so that optical acquisition was required. Transmission measurements are continuing at the date of writing this report.

4.2 TRACKING ACCURACY

4.2.1 General

One method by which dynamic tracking error in a satellite tracking system can be measured is to photograph a visible satellite, using a camera that has been aligned with the electrical axis of the antenna. This measurement can be performed while the system is tracking at its normal range under typical operating conditions and permits an accurate assessment of total error under these conditions. Tracking accuracy measurements have been performed on the 84-foot tracking radar at the Trinidad Site and in two of the three tracking modes at the Floyd site to determine the adequacy of tracking accuracy for the 2-gc communications experiments.

A boresight camera enclosed in a weatherproof housing has been provided at each site. These cameras are aligned with the antenna electrical axes and permit photographic measurement of tracking error when tracking an optically visible satellite at night or under simulated tracking conditions utilizing a beacon-carrying aircraft during the day. This technique of tracking error measurement is, of course, restricted to clear weather conditions.

The boresight facilities utilize Robot semi-automatic cameras equipped with 650-mm $f/5.5$ lenses. For satellites of the Echo I or Echo II class, an exposure of $1/4$ second per frame and Tri-x film are utilized. This permits convenient identification of objects down to third optical magnitude, or about $1/20$ th the brilliance of the Echo I satellite at zenith.

The Robot semi-automatic boresight camera is equipped with automatic film advance and a solenoid-operated shutter release, permitting operation by means of a timer remotely located in the equipment building at either site. This timer is normally operated by the one-pps pulses from the digital readout of the electronic counter at each site; thus an automatic frame rate of one-per-second is established. Incorporated in the boresight camera is the secondary image prism, which provides a reference presentation in one corner of each picture frame. This reference field includes miniature antenna elevation and azimuth readouts, a frame counter, and at Floyd a series of indicator lights designating the tracking mode in use. Typical photographs taken through the Trinidad boresight camera are illustrated in Figure 4-1.

In the Trinidad measurements, the camera was first aligned with the electrical boresight of the antenna by directing the antenna toward a target antenna 16,000 feet distant and taking a series of photographs. The image of the target antenna was then used as a reference in reducing the data. This absolute axis calibration permitted resolution of the measured error into

systematic and nonsystematic components. In the case of the Floyd measurements, axis alignment was derived from ephemeris data on the sun, while tracking passively on solar noise. In each case, an angular-error-magnitude calibration was obtained by photographing the full moon. The apparent diameter of the moon is tabulated in the American Ephemeris and Nautical Almanac, permitting an accurate angular calibration of the photographic field.

4.2.2 Floyd Optical Tracking Accuracy

On October 19, 1961 two visible passes of 1960 Iota 1 (Echo I revs. 5318, 5319) were tracked optically while photos were taken at the rate of 1 per second. The first pass occurred at approximately 0315 EST and the second pass at 0520 EST. Maximum satellite elevation on the first pass was approximately 40° , while the second pass reached an elevation of between 70 and 80° . The optical tracker was operated by one of the Floyd Site personnel, and this was his first attempt at tracking a satellite optically.

In all, some five hundred usable photographs were taken during the two satellite passes. These were analyzed by projection on a screen calibrated in the degrees error and scaling the points in the form of scatter plots. From the scatter plots it was possible to compute a distribution of error magnitudes.

Figure 4-2 is a scatter plot of 130 consecutive points taken during the second satellite pass. The points plotted here were taken near the maximum satellite elevation and are typical of performance at maximum apparent satellite velocity.

The second satellite pass was further analyzed for distribution of tracking error magnitudes and this distribution is presented in Figure 4-3. Examination of Figure 4-3 shows the median total error to be 0.12 degree. An error of 0.22 degree was exceeded 10 percent of the time and an error of 0.32 degrees was exceeded 1 percent of the time.

The rms tracking error resulting from the sum of optical tracker pointing error and antenna following error is 0.12 degrees. By computation from the Floyd antenna pattern at 2.27 gc, this error represents an rms signal degradation of 0.5 db and the introduction of 1.4 db of peak-to-peak fading. The measurement discussed here was performed without practice and on a cold night before the windbreak was erected around the optical tracker. Subsequent experience has indicated that an experienced operator should be able to track an optically visible satellite at an rms error appreciably below 0.1 degree.

4.2.3 Floyd Radar Tracking Accuracy

The initial 425-mc monopulse tracking system was retained intact, but its tracking performance was not measured since it had been reported earlier.² Operational experience with the monopulse tracking equipment indicated that its tracking accuracy on a slowly moving target and at a signal level comparable to the un-degraded Echo I satellite, was of the order of ± 0.3 degree rms. Since this is well within the pull-in range of the 2-gc tracking feed, the radar system remains a valuable acquisition aid.

4.2.4 Floyd 2-gc Tracking Accuracy

The 2-gc tracking equipment at Floyd provides the most accurate performance of the three tracking modes. Because of lack of availability of the tracking antenna at Trinidad, it has not been possible to make photographic measurements on an Echo satellite pass using that tracking mode. Photographic measurements with the Echo I or II satellite will be made as soon as possible; meanwhile it has been necessary to make passive measurements at the Floyd site to establish the 2-gc tracking capability. These measurements were performed by passively tracking the sun on solar noise, and comparing the instantaneous pointing angle at 1-second intervals with interpolated solar ephemeris data. The results are considered to be representative of performance with the Echo satellites, since (a) the signal levels are comparable, and (b) although the solar tracking rate is lower, the Echo tracking rate is still sufficiently low as to introduce no appreciable velocity error.

Figure 4-4 is a scatter plot of 276 consecutive points during a typical solar track. The points plotted were taken in early afternoon, and they represent an average value of solar elevation.

The data plotted in Figure 4-4 were further analyzed for distribution of tracking-error magnitudes. This distribution is presented in Figure 4-5. The median tracking error is 0.04 degree, while an error of 0.08 degree is exceeded 10 percent of the time, an error of 0.13 degree is exceeded 1 percent of the time. These error magnitudes indicate no measurable performance degradation due to tracking at Floyd.

4.2.5 Trinidad Tracking Accuracy

A series of photographic measurements similar to those described in the preceding paragraphs was performed on the Trinidad antenna. These measurements were made on 1960 Iota 1 (Echo I, revs. 3674, 3675) using the AN/FPT-5 radar for tracking. The tracking accuracy was found to be satisfactory for all satellite elevations of interest, resulting in no measurable 2-gc performance degradation. Full details of the measurements, along with quantitative tracking accuracy data were presented in an earlier report.¹⁷

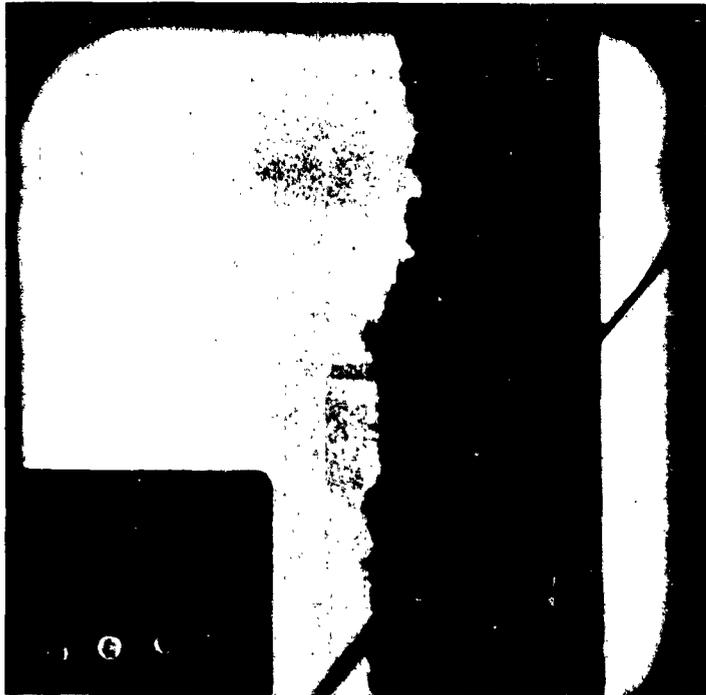


Figure 4-1. Typical Photographs Through Boresight Camera

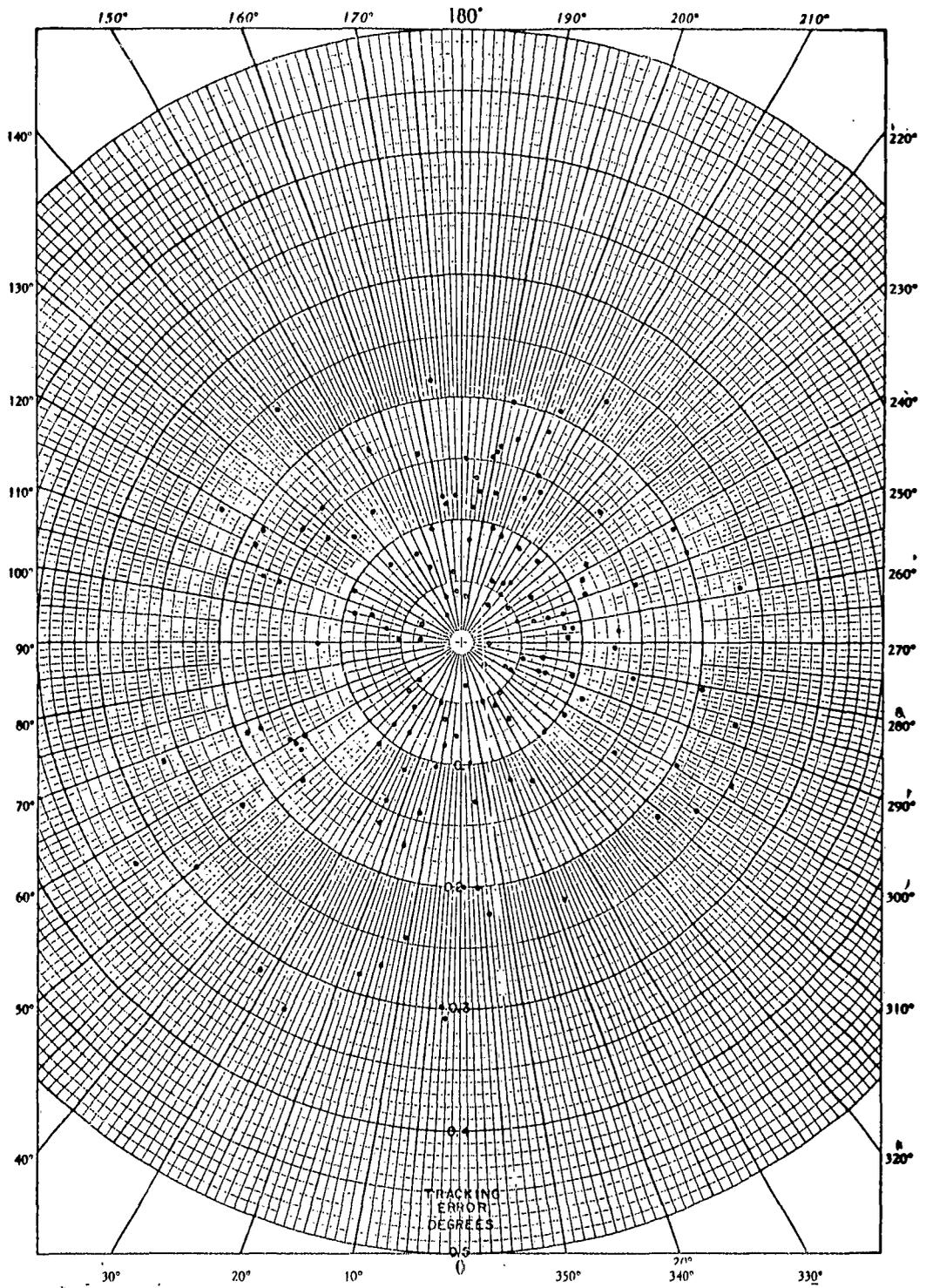


Figure 4-2. Scatter Plot of Optical Tracking Accuracy, Floyd Site

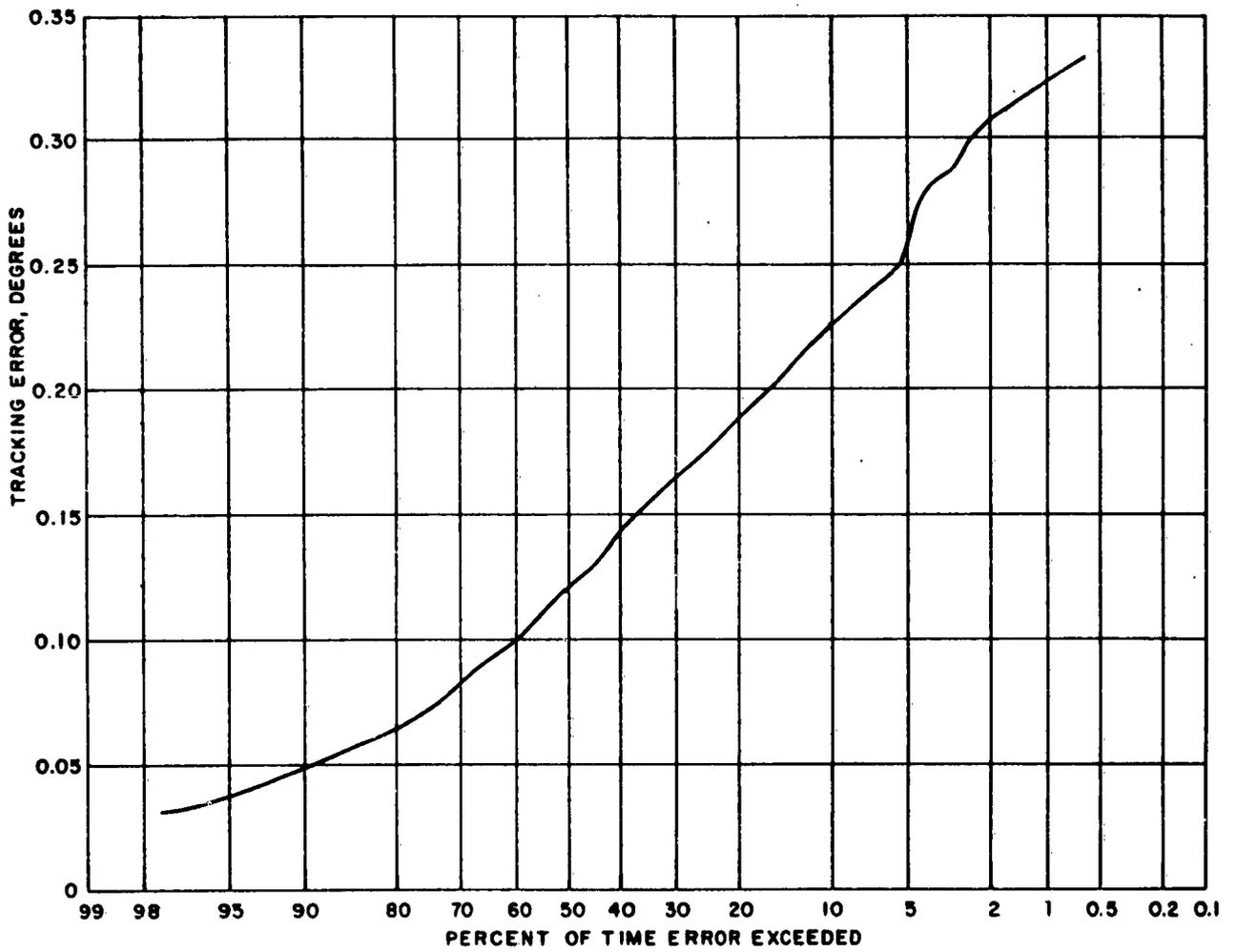


Figure 4-3. Distribution of Optical Tracking Errors, Floyd Site

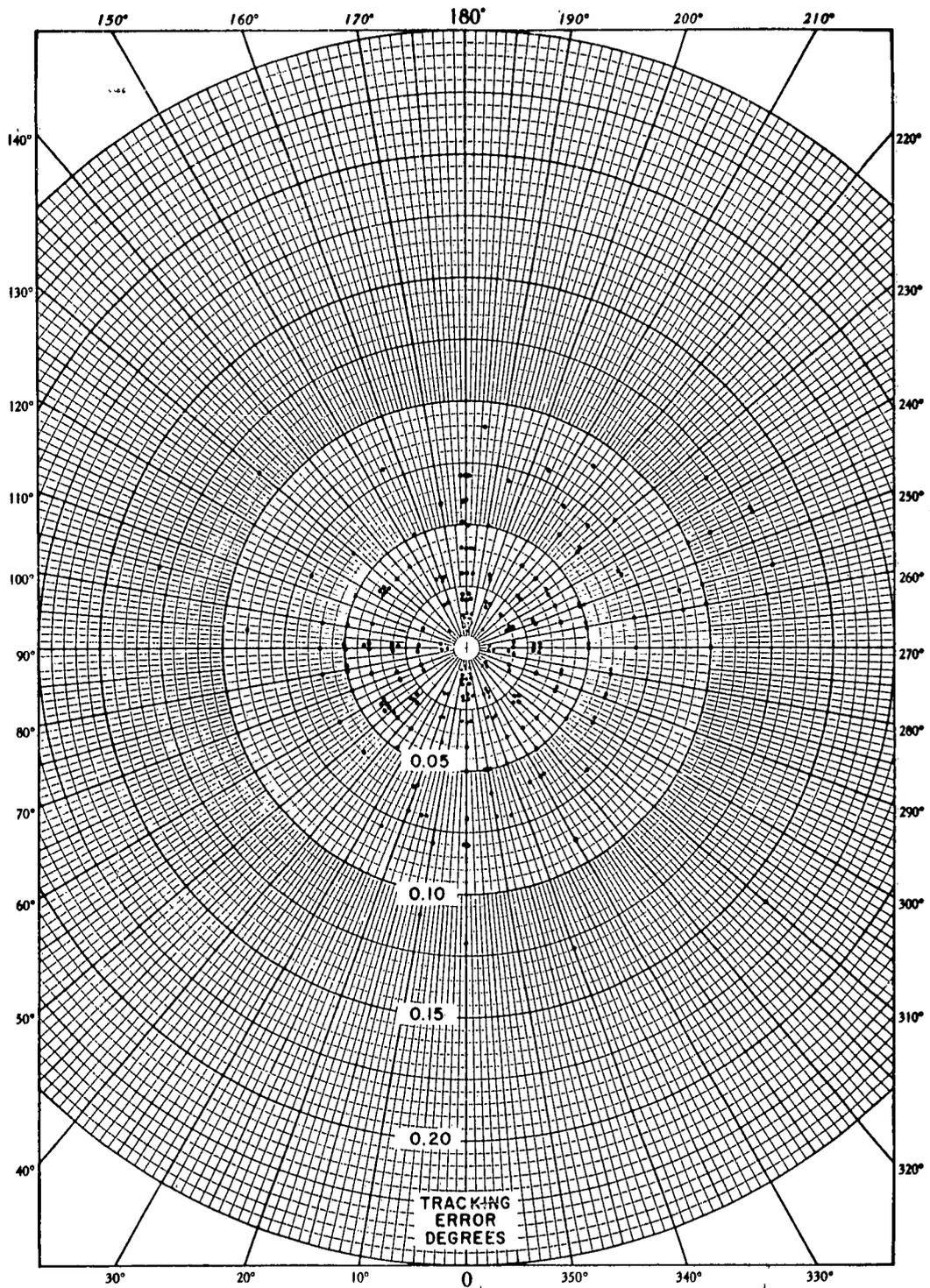


Figure 4-4. Scatter Plots of 2-GC Tracking Accuracy, Floyd Site

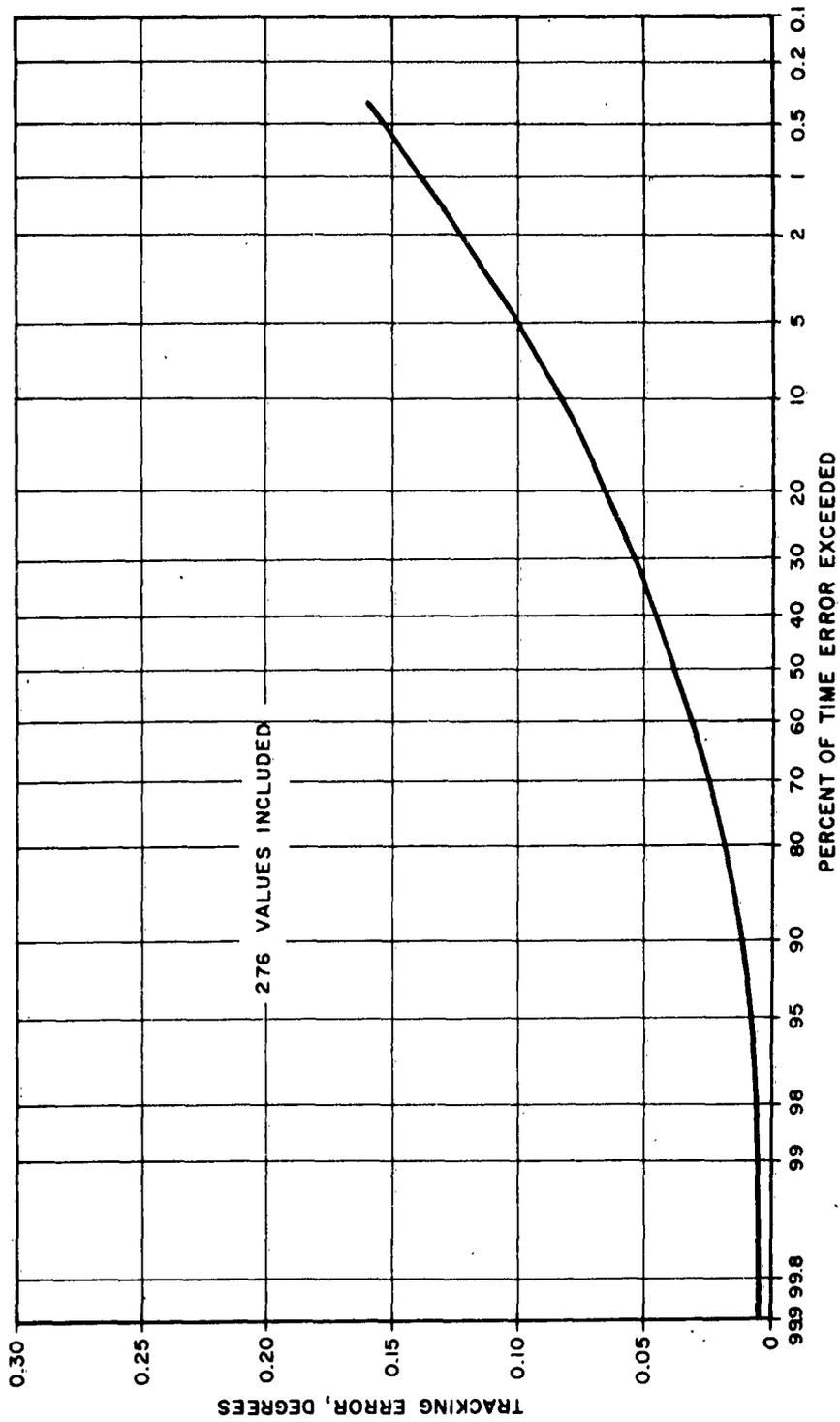


Figure 4-5. Distribution of 2-GC Tracking Errors, Floyd Site

SECTION 5
60-FOOT CASSEGRAIN REFLECTOR

5.1 GENERAL

A 60-foot Cassegrainian Reflector System, Figure 5-1, was procured by subcontract from Advanced Structures Division, Telecomputing Corporation, of La Mesa, California. This reflector was delivered to RADC Floyd Site, and assembled and adjusted on the ground. Its initial use at the Floyd Site will be by the Hughes Aircraft Company in connection with another contract.

The primary reflector is of Advanced Structures proprietary TETRAC design. TETRAC is an abbreviation of Tension Truss Antenna Concept, which refers to the prestressed radial and circumferential trusses used in the reflector backup structure. The reflector's solid surface is made of a number of contoured panels of aluminum honeycomb core, sandwiched and epoxy-bonded between aluminum skins. A circular opening, 5 feet in diameter is provided at the vertex of the reflector to accommodate a feedhorn assembly (not part of the reflector system as provided).

The secondary reflector is in the shape of an hyperboloid of revolution 5 feet in diameter at its base. It is of self-supporting sandwich design, utilizing epoxy-fiberglass laminate facings over an aluminum honeycomb core. The exterior surface is metalized with aluminum.

The secondary reflector is supported in position by four tapered steel spars.

5.2 PARAMETERS

The following parameters define the 60-foot reflector system:

Weight	17,979 lbs
Center of gravity	127 inches forward of mounting frame

Frequency range	1.7 to 8.4 gc
Primary Reflector	
Equation	$y^2 = 1200 x$
Diameter	720 in.
Focal length	300 in.
F/d	0.417
Secondary Reflector	
Equation	$x = 89.4706 \sqrt{1 + (.0132808y)^2} - 1$
Diameter	69.6 in.
Depth	9.09 in.
Weight	61 lb

5.3 TOLERANCES

5.3.1 Primary Reflector

Three tolerance requirements are placed on the primary reflector.

These requirements are that:

- a. The primary reflector surface remains within ± 0.062 in. rms of the theoretical paraboloid as measured parallel to the axis of revolution for all static positions of the reflector assembly under ambient temperatures of -30 to 130°F , with wind velocities ranging from zero to 20 mph.
- b. The primary reflector surface has a deviation tolerance of 0.036 in. rms as computed from measurements made at 500 different points on the surface.
- c. The primary reflector surface has a maximum deviation of ± 0.125 in. under all environmental conditions including maximum angular acceleration of $5^{\circ}/\text{sec}^2$.

5.3.2 Secondary Reflector

The secondary reflector has a 0.030 in. rms surface tolerance of deviation from the theoretical hyperboloid. It is supported by a quadripod spar structure on adjustable mounts, and remains in its adjusted position within the following tolerances:

- ± 0.020 in. axial translation
- ± 0.030 in. lateral translation
- ± 0.01° angular deviation

5.3.3 Collimator System

The two-target collimator of the primary reflector and the auto-reflection target collimator of the secondary reflector permit the relative alignment of the primary and secondary reflectors within the following tolerances:

- ± 0.030 in. lateral displacement of axis of secondary reflector from axis of primary reflector
- ± 0.025° angular displacement of axis of secondary reflector with respect to axis of primary reflector

A removable two-target collimator is provided for the primary reflector. The collimator mounts at the vertex of the reflector in three accurately located and machined guide holes. It defines the axis of revolution of the primary reflector to within ± 0.002 in. lateral displacement and ± 10 sec of arc angular deviation.

A removable autoreflexion target collimator is provided for the secondary reflector. It mounts at the vertex of the reflector in a single accurately located precision tool bushing. The collimator is located concentric with the axis of revolution of the secondary reflector within ± 0.002 in. and is parallel to this axis within ± 10 sec of arc.

5.3.4 Contour Checking Equipment

A Wilde Theodolite, which mounts in the same set of three guide holes provided for the primary reflector collimator, is provided to verify the contour of the primary reflector. This instrument is used with the reflector system in the zenith pointing position. By comparing readings taken of the angular position of known targets on the surface of the reflector with tabulated values of these angular positions, one can determine whether the surface is still in alignment. Quantitative measurements cannot be made because this instrument permits reading of only one angular coordinate.

5.4 ACCEPTANCE TESTS

5.4.1 General. On site measurements have demonstrated the realization of the design parameters discussed in the preceding paragraphs. These tests and measurements are detailed in the reports listed in paragraph 5.4.2.

5.4.2 Test Reports

- a. Advanced Structures Report No. 62-006, 14 June 1962, "Evaluation of the Page 60' Diameter Parabolic Reflector."
- b. Advanced Structures Report No. 61-018, undated, "60' Reflector Static and Environmental Deflection Analysis."
- c. Extract of Advanced Structures Letter, file 81-FLS-6.243, 29 June 1962.
- d. Advanced Structures Report, 11 May 1962, "Contour Checking Procedure."
- e. Advanced Structures Report, undated, "Method of Manufacture and Inspection of Hyperbolic Sub-reflector Tool P/N 20054."
- f. Advanced Structures Report, 11 May 1962, "Report of Secondary Reflector Field Contour Inspection."

- g. Advanced Structures Report No. 61-030, 18 October 1961, "Page Sub-reflector System Analysis."
- h. Extract, Advanced Structures Letter, file 81-FLS-6. 243, 29 June 1962.
- i. Advanced Structures, Report of Field Supervisor, 11 May 1962, "Sub-dish position, 60' Page Tetrac."
- j. Advanced Structures Report No. 61-045, 27 November 1961, "Calculated Weight Report."

SECTION 6

CONCLUSIONS

The principal objective of the program, the establishment of a duplex passive satellite communication test facility, has been achieved. In achieving this objective, the following significant conclusions can be drawn:

- (a) Full duplex operation, utilizing the same tracking antenna for transmitting and receiving, can be practically implemented without serious degradation of low-noise receiving capability. In this case, no duplexing noise and only 0.3 db filter insertion loss resulted.
- (b) Artificial conical-scan techniques, utilizing a four-horn cluster, provide a practical means of deriving tracking information from the received frequency while simultaneously transmitting a non-scanned beam at high power.
- (c) Use of a tuned, artificial dielectric sheet as a Cassegrain sub-reflector provides a convenient means of dual-frequency excitation of a single tracking aperture without mutual degradation, provided sufficient frequency separation exists.
- (d) The use of highly sensitive receiving system in the same aperture with a megawatt-level radar tracking system is practical with proper choice of frequencies.
- (e) The tracking accuracy of both the Trinidad AN/FPT-5 radar and the Floyd 2-gc feed are satisfactory to introduce negligible degradation into system performance.

SECTION 7 RECOMMENDATIONS

7.1 GENERAL

The purpose of the program described in this report was to provide an interim duplex facility for conducting communications experiments with passive satellites of the Echo type. The facilities described here provide this capability. During the course of the program, however, a number of possible improvements have come to light, particularly in the areas of acquisition and baseband signal-to-noise ratio improvement. These potential improvements are detailed in the paragraphs which follow.

7.2 FLOYD RADAR-TRACKING IMPROVEMENTS

The threshold sensitivity of the 425-mc monopulse tracking system at Floyd is approximately -127 dbm. Although this sensitivity was marginally adequate for tracking the Echo I satellite at the time of its launch, the fading signal now obtained lies below this threshold even after the improvement of the spiral antenna feeds was made. Although a communications-frequency tracking system (described in paragraph 2.2.5.3) has been incorporated in the system, the 425-mc radar tracking facility remains an important mode of satellite acquisition.

Acquisition of a satellite in the radar-tracking mode is considerably easier than in the communication-tracking mode for two reasons. First, the ratio of approximately 5 to 1 between the frequencies of the communications and radar signals results in a 5-times greater antenna beamwidth at the radar frequency. Although this greater antenna beamwidth implies a lesser ultimate tracking accuracy, it also provides a proportionally greater angular acquisition range. Secondly, the greater doppler shift associated with the 2-gc communications signal and the narrow bandwidth of the 2-gc communications

receiver complicate acquisition in the communications-tracking mode. It would therefore be desirable to reduce the threshold of the radar-frequency tracking system so that it can be used successfully to acquire the Echo I satellite in its presently degraded condition and other possible objects having similar or lesser signal return. Threshold reduction would also provide a more satisfactory operating margin to allow for pass-to-pass variation.

The noise figure of the present 425-mc tracking system is approximately 4.5 db. Taking into account line losses and antenna temperature, incorporation of 1-db parametric amplifiers would result in a threshold reduction of approximately 4.3 db. Stable, uncooled, 1-db parametric amplifiers are now procurable for the 425-mc frequency range.

A second possible improvement offering even greater values of threshold reduction involves reduction of the predetection bandwidth in the radar-tracking receiver. In the present radar-frequency tracking receiver, azimuth and elevation signals are used to control the amplitudes of 10 and 15-kc sidebands so that a common IF amplifier can be used for the composite df signal. The IF bandwidth utilized is 50 kc, to permit all sidebands of the composite df signal to pass and to leave sufficient space on either side to accommodate the maximum doppler shift anticipated. After a baseband detection, the subcarriers corresponding to the individual error voltages are filtered in narrower filters and detected. In a system of this type, however, the threshold is determined primarily by the noise amplitude in the first predetection bandwidth, in this case 50 kc. Insertion of a narrower carrier filter would significantly reduce the threshold with respect to the monopulse sum signal. AFC could be incorporated to follow doppler shift. Replacement of the AM envelope detector with a synchronous detector operating against the detected sum-channel signal would then permit the existing postdetection sideband filters to determine the error-signal thresholds. It is probable

that an overall threshold reduction greater than 10 db could be achieved by these simple modifications.

7.3 COMMUNICATIONS BASEBAND DEMODULATOR IMPROVEMENTS

Because of the extremely high path losses involved in communication by passive satellite reflection, high-gain antennas, high-power transmitters and very sensitive receivers are required to provide even the basic single-voice-channel communications system. The provision of improved signal-to-noise ratio and or additional channels by increasing antenna gain or transmitter power becomes increasingly difficult, both practically and economically. Thus, full utilization of an advanced modulation and detection system is particularly desirable on passive satellite systems as an economical means of achieving significant improvements in channel signal-to-noise ratio. Future operational system will require the use of these or similar techniques to realize their full communications potential.

Recent investigations have disclosed several promising techniques for the reduction of threshold in FM systems. In baseband demodulation, threshold reduction techniques have as their general objective making the threshold-producing noise depend not on the IF bandwidth, but rather on the baseband width. This not only produces the possibility of threshold reduction, but also makes possible the selection of FM improvement factor independently of threshold considerations. Thus, for an IF bandwidth of $2F$, a top baseband frequency B and receiver noise figure N :

$$\begin{aligned} \text{Maximum available FM index} &= \frac{F}{B} \\ \text{Maximum available FM improvement factor} &= 3 \left(\frac{F}{B}\right)^2 \\ \text{Threshold (FM)} &= 2 \text{ kTFN} + 9 \text{ db} \end{aligned}$$

$$\text{Threshold (phase-lock)} = 2 kTBN + 9 \text{ db}$$

$$\text{Maximum available threshold reduction} = \frac{F}{B}$$

Phase-lock detection²⁰, FM feedback^{21, 22}, and regenerative IF frequency division²³ constitute somewhat comparable techniques for threshold reduction. A fourth technique, the oscillating limiter²⁴, also offers some possibility of threshold reduction, although not to the extent of the first three. Of these, phase-lock appears the most desirable when considering the potential improvement and practical details of physical realization.

In a single-channel system when intermodulation distortion is not a great problem, the amount of baseband signal-to-noise ratio improvement with phase-lock detection is potentially very great. For example, if a deviation ratio of 10:1 could be used, the resulting baseband signal to noise ratio improvement would be 20 db without any reduction of threshold. For a multi-channel system where intermodulation must be held to very low values to prevent crosstalk, practical operational phase-lock systems are realizing as much as 6-db threshold reduction. The application of phase-lock detection to the Floyd-Trinidad facility is recommended as one of the most economical methods of providing substantial baseband signal-to-noise ratio improvement.

7.4 DOPPLER SHIFT TRACKING IMPROVEMENTS

Apart from the usual problems associated with long haul communications systems, the use of satellite reflectors introduces the additional variable of doppler shift. Since the satellite trajectories in the useful reflecting intervals constantly change, the apparent frequency as received follows a continually changing pattern. Although this pattern may be predicted with some accuracy, minor perturbations and errors in data will always result in a non-trivial error. As a result, any communications system envisioned at present

must have some means of accepting and correcting for this frequency shift. Since it is necessary to restrict bandwidth to the minimum possible, to recover the feeble signals from a background of noise, it is not practical to permit a system bandwidth large enough to accept the total anticipated carrier excursion due to the doppler shift. The phase-lock technique²⁵ utilized in the Floyd and Trinidad receivers provides automatic frequency tracking for satellite-reflected signals whose frequencies are slowly changing. Phase-lock tracking of the received carrier also provides for accurate measurement of the doppler shift, as well as permitting predetection diversity combining.

A further refinement of this technique can now be suggested. The maximum possible doppler shift on the Floyd-Trinidad circuit using a carrier frequency of 2-gc with the Echo I satellite is somewhat in excess of 100 kc. As a result of various effects, the anticipated maximum fluctuation from the predicted received frequency is of the order of 10 kc. The receiver must, however, accommodate the total excursion of greater than 100 kc in order to track the satellite from horizon to horizon. This dictates the range required of the voltage-controlled oscillator in the phase-lock receiver. The requirement on the controlled oscillator is precisely the requirement that the oscillator sensitivity be high. This high oscillator-sensitivity requirement places a restriction on the minimum loop bandwidth which can be achieved with a practical loop filter. In the case of the Floyd and Trinidad receivers, this bandwidth is approximately 100 cps.

Since orbital data is available, it is possible to anticipate the received frequency and program the receiver closely to this expected frequency. Such a programmed change in local oscillator frequency would permit a reduction in bandwidth of a order of magnitude, by permitting a corresponding reduction in oscillator sensitivity. With this system the oscillator control need only be large

enough to handle the maximum expected variations from the predicted values. A programmed doppler tracking system is of particular interest, since it will result in an improvement in the ability of the system to weather protracted signal fades and dropouts.

In an unprogrammed system, the oscillator is of necessity sensitive to small changes in control voltage. As a result, if a signal dropout occurs, the control voltage will tend to decay towards a zero-error state, even though the oscillator may have had a significant correcting voltage applied to it prior to the signal loss. Thus a loss of signal for even a short time may result in slight decay in control signal which, with the high sensitivity of the oscillator, might shift the tuning of the receiver appreciably. This shift might be sufficient that when the signal reappears it would be outside of the relatively small capture range of the receiver and would be lost. A distinct improvement results when a programmed receiver is used. If the signal drops out, the oscillator will drift much more slowly, its sensitivity having been reduced by an order of magnitude from that of the nonprogrammed receiver. Further, the drift is not towards the same zero-error state as the nonprogrammed receiver, but toward the currently predicted setting. Thus when the signal reappears, the receiver is "anticipating" it to the best of the ability of the program to predict it.

After reception of the signal for some time, corrections can probably be made to the program data on the basis of experience. A study of Echo-tracking experiments versus predicted data shows exactly this effect. A human operator if experience showed the predicted data to be consistently, say 10 kc low, would extrapolate from his own experience and tune 10 kc higher than predictions, achieving better results. This procedure can also be automated, resulting in an adaptive doppler-tracking system. The essential component of any adaptive system is an element that can assess the accuracy that has been achieved in following the input variation. This

assessment of the accuracy would determine the degree of confidence that can be placed in correction data derived from it. The incorporation of an adaptive doppler-tracking system into the Floyd and Trinidad receivers is recommended, to improve the ability of the phase-lock system to withstand signal perturbations and dropouts and to facilitate acquisition and re-acquisition of the signal.

7.5 FLOYD ANTENNA SIZE INCREASE

A very straightforward, although relatively expensive method of increasing the sensitivity of both the tracking and communications systems, would be through an increase in the diameter of the Floyd antenna. Replacement of the present 33-foot reflector with another reflector of 60-foot diameter would result in a sensitivity improvement of 5.2 db. Soil and concrete borings at the Floyd site have indicated that the present tower is capable of supporting a 60-foot solid-surface tracking dish, provided certain structural modifications in the tower walls and footings are made.

7.6 FSK MODEM FOR LUNAR DATA TRANSMISSION

Baseband AFSK tone keyers and demodulators are provided at the Floyd and Trinidad sites for teleprinter or data transmission. While this mode of transmission is satisfactory for a relatively unperturbed medium such as artificial satellite reflection, the severe perturbations resulting from lunar reflection reduce the effectiveness of AFSK/FM transmission. Selective fading introduced by the lunar reflection between the sidebands and carrier of the FM signal introduces severe distortion. Selective fading between mark and space frequencies also results in increased error rates when a fixed FSK threshold is used. Both of these effects are quite severe in lunar transmission where the correlation bandwidth is only a few hundred cycles²⁶.

For the transmission of teleprinter data using the lunar mode of propagation, it is recommended that direct frequency shift keying be used as a modulation method, since this technique is well developed and has been successfully used in other lunar experiments. It is recognized that AM could be used for this purpose, but the error-rate performance would be severely degraded, due in part to the difficulty of setting the decision threshold. A recently developed technique²⁷ is available, which substantially reduces the high error probability resulting from frequency-selective fading. This technique, designated the Decision Threshold Computer (DTC) makes use of the frequency-selective fading to provide additional orders of diversity. For example, when used for the reception of FSK signals from two receivers in space or polarization diversity the DTC effectively results in 4th-order AM diversity. To provide an efficient system for lunar data transmission, incorporation of direct FSK modems, with DTC, into the Floyd-Trinidad facility is recommended.

SECTION 8
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APPENDIX I

CALCULATION OF SATELLITE PATH-LOSS PROFILES

The attenuation between isotropic antennas for relay by means of a passive satellite can be written:

$$L_p = \frac{4^2 R_1^2}{\lambda D} \cdot \frac{4^2 R_2^2}{\lambda D} \quad (1)$$

in which λ is the wavelength, D the satellite diameter, R_1 the slant range to the satellite from the one antenna, and R_2 that from the other. Figure I-1 shows the pertinent geometry, including S , the projected length along the earth's surface of the slant range R .

In the formula above, the two factors are conveniently thought of as the "loss going up" and the "loss coming down." The locus on the earth of the projection of a particular slant range, and consequently of a particular one-way loss, is a circle centered on the ground antenna. Thus, it is convenient to draw a system of circles about each site and to label each with the pertinent one-way loss. The total system of two families of circles then constitutes a system of curvilinear coordinates from which the total two-way loss can be read for any hypothetical satellite position. Or, alternatively, on these coordinates may be traced out various loci of constant loss.

R and S have been related by

$$R^2 = r^2 + (r + h)^2 - 2r(r + h) \cos \frac{S}{r} \quad (2)$$

where r = earth's radius,
 h = satellite height.

The earth is assumed to be a perfect sphere, as that is quite adequate for present pictorial purposes. The use of a stereographic map projection based on a point near the midpoint of the sites minimizes difficulty with map metrics used over rather large areas.

Figure I-2 is a curve showing the one-way loss as a function of projected slant range S , for a satellite of 135-foot diameter in circular orbit at 650 nautical miles.

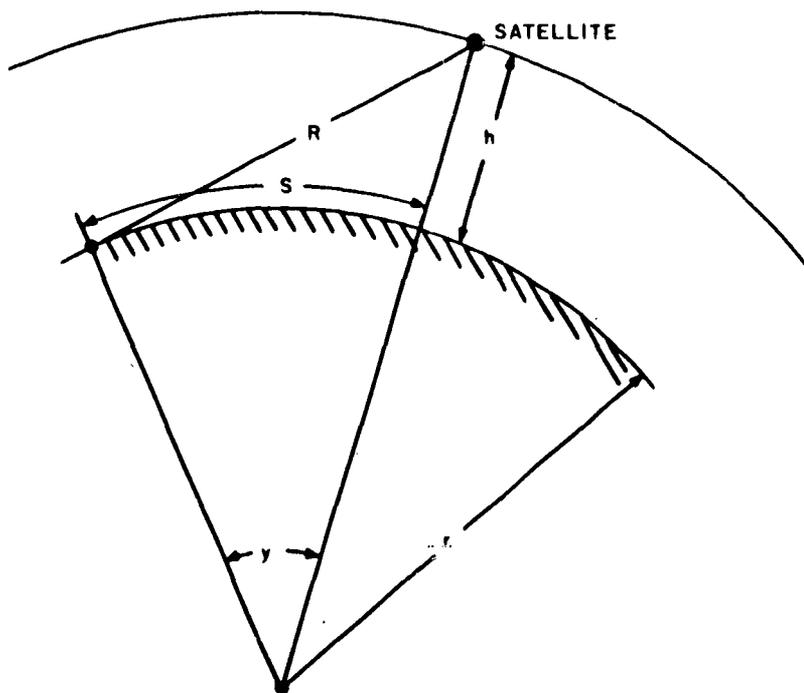


Figure I-1. Geometry for Conversion of Slant Range to Surface Distribution

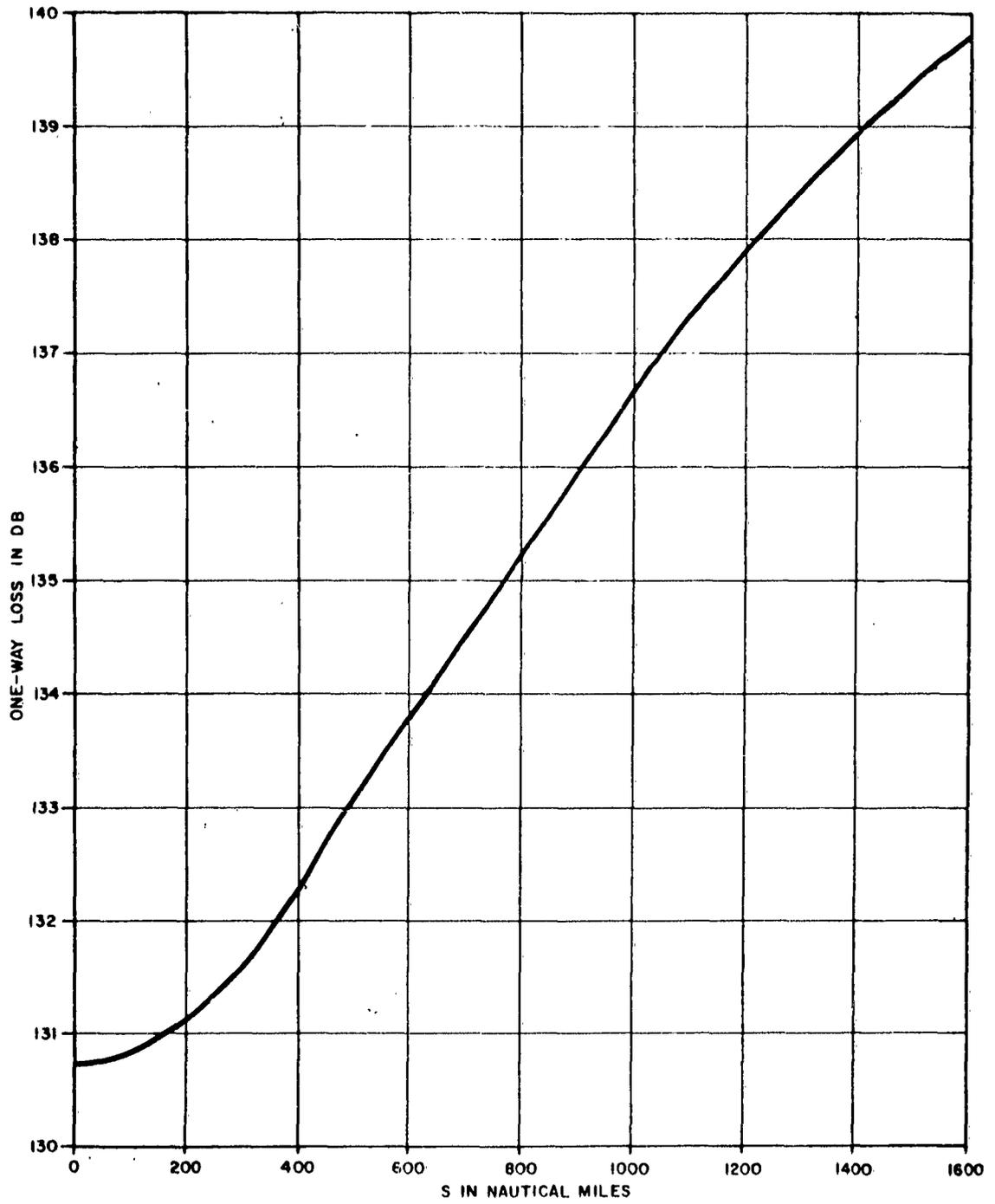


Figure I-2. One-Way Path Loss vs. Projected Slant Range, Echo II Satellite

APPENDIX II
LIST OF MAJOR ITEMS OF SYSTEM AND
TEST EQUIPMENT

1. Page-Furnished Equipment

<u>Description</u>	<u>Floyd Site</u>	<u>Trinidad Site</u>
Amplifier, dual channel parametric, 1.7-2.4 gc, Airborne Instruments Laboratory type 9321	1	1
Amplifier, power, 10 kw, 2-gc, REL type 989	1	0
Amplifier, 452-mc, Applied Research Inc. model UH-2(A)	0	1
Camera assembly, boresight, PCE-E-8316	1	1
Cooling system, liquid nitrogen, PCE-S-8405	1	1
Demodulator, conical scan, PCE-S-8391A	1	0
Converter amplifier, 2-gc, dual-channel, Microphase Corp.	1	1
Exciter, UHF, REL Type 867C	1	0
Feed System, 33-foot reflector, 2-gc dual- polarized, conical scan, Radiation Systems Inc. PCE-S-8801A	1	0
Feed System, 84-foot reflector, 2-gc dual- polarized, Antenna Systems Inc., PCE-S-8107	0	1
Filter, antenna duplexing, 1.7-2.4 gc, Antenna Systems Inc., PCE-S-8094A	1	1
Filter, antenna receiving, 1.7-2.4 gc, Antenna Systems Inc., PCE-S-8093A	2	1
Meter, carrier deviation, Marconi TF 791D	1	0
Meter, microwave power, Sperry model 123B	1	0

<u>Description</u>	<u>Floyd Site</u>	<u>Trinidad Site</u>
Optical tracker system	1	0
Pulse modulator, hard-tube, Amicon Corp. ATR-1	0	1
Receiver, phase-lock, dual-diversity, PCE-M-9688A	1	1
Recorder, tape, Ampex 960	0	1
Recorder, strip chart 8-channel, Brush RD-1684-00	1	0
Regulator, voltage, 110 v ac 60-cps, General Radio type 1570-ALS15	1	1
Shelter, RF equipment, antenna-mounted PCE-D-8454	0	1
Synthesizer, frequency, Page Type F, PCE-M-9389A	1	0
Synthesizer, frequency, Page Type T, PCE-M-9388A	0	1

2. Government-Furnished Equipment

<u>Description</u>	<u>Floyd Site</u>	<u>Trinidad Site</u>
Amplifier, dual-channel, parametric, 2.27-gc, Philco	0	1
Amplifier, power, 10-kw, 2-gc, REL type OA-150 3/FRC 56	0	1
Amplifier, antenna drive servo, Philco	1	0
Amplifier, twt, Alfred Electronics Model 510	1	0
Amplifier, IF, General Radio 1216-A	1	0

Description	Floyd Site	Trinidad Site
Atomichron, National Company type NC 1001A	1	1
Counter, frequency, Hewlett-Packard 524D with frequency converters 525A and 525B	1	1
Converter amplifier, 2-gc, REL CV-580/FRC-56	2	0
Converter, VHF, Nems-Clark REV-100	1	0
Distortion analyzer, Hewlett-Packard 330B	0	1
Duplexer, 2-gc, Sperry CD-567/U	0	1
Exciter, UHF, REL type OA-1503/FRC-56	0	1
Generator, pulse, Rutherford B 7	0	1
Generator, VHF, Hewlett-Packard 608C	3	0
Generator, sweep frequency, Kay Vari-Sweep	0	1
Generator, UHF, Hewlett-Packard 616B	0	1
Generator, UHF, TS 403/U	1	0
Keyer, Northern Radio 153	0	1
Meter, noise figure, Hewlett-Packard 340B	1	0
Meter, microwave power, Hewlett-Packard 430C	0	1
Noise source, hot and cold body, AIL Type 70	1	1
Oscillator, Hewlett-Packard 650A	1	1
Oscillator, Hewlett-Packard 200 CD	1	1
Oscilloscope, Tektronix 515A	0	1

Description	Floyd Site	Trinidad Site
Oscilloscope, Tektronix RM 16	1	0
Preamplifier, Tektronix	1	0
Power supply, Dressen Barne	1	0
Power supply, Lambda 281 and 281M	5	2
Power supply, Dynapack model 201 RPS	1	0
Receiver, df system, Philco	1	0
Receiver, SP600	2	2
Receiver, R 390/URR	0	1
Receiver, R 390A/URR	3	1
Recorder, digital, Hewlett-Packard 560A	1	1
Recorder strip chart 8-channel Brush Type RD-1684-00	1	0
Recorder strip chart 6-channel Brush Type RD-1664	0	1
Recorder, tape Ampex 960	2	1
Receiver, boresight, 2. 27-gc. Philco	0	1
Receiver, UHF, crystal mixer Philco	1	0
Synthesizer, frequency, Schomandl type ND5 with NB7 amplifier	0	1
Synthesizer, frequency, Schomandl type FD3 with power supply, Stage A, and Stage B	1	0
Speaker-amplifier, Ampex 2010	2	1
Telegraph terminal, Radio Frequency Labs type RFL 995	1	1
Tone converter, Northern Radio 152	1	0
Tester, tube, Hickok 1575	0	1

<u>Description</u>	<u>Floyd Site</u>	<u>Trinidad Site</u>
Transfer oscillator, Hewlett-Packard 540B	1	0
Voltmeter, vacuum tube, Hewlett-Packard 400D	1	1
Voltmeter, vacuum tube, Hewlett-Packard 410B	0	1
Voltmeter, RMS, Ballantine 320	0	1
Voltmeter, Simpson 270	2	1

APPENDIX III
DOPPLER SHIFT COMPUTATIONS

The doppler frequency shift in a transmission via passive satellite consists of two components: The frequency transmitted to the satellite is shifted, and that shifted frequency is again shifted upon reflection to the receiver. To a very good first approximation, however, this may be considered as two simple shifts of the transmitted frequency. Thus, for a transmitted frequency f_t the shifted frequency f'_t is

$$f'_t = f_t \left(\frac{c + v_1}{c - v_1} \right) \left(\frac{c + v_2}{c - v_2} \right) \quad (1)$$

$$f'_t \approx f_t \left(1 + \frac{2v_1}{c} + \frac{2v_2}{c} + \frac{4v_1 v_2}{c^2} \right) \quad (2)$$

$$f'_t \approx f_t \left(1 + \frac{2v_1}{c} + \frac{2v_2}{c} \right) \quad (3)$$

The total doppler shift f_d is

$$f_d = f_t \left(\frac{2v_1}{c} + \frac{2v_2}{c} \right), \quad (4)$$

where:

c = the velocity of light,

v_1 = the component of satellite velocity along the line from the satellite to site 1, and

v_2 = the component of satellite velocity along the line from the satellite to site 2.

The total shift can be interpreted as the "one-way shift" on the way up plus the "one-way shift" on the way down.

Representing the total doppler shift as the sum of two one-way shifts, it is feasible to prepare a map of iso-doppler-shift contours about each site. For any direction of satellite travel, two families of curves are prepared, which have rather the appearance of hyperbolas. These provide a two-coordinate curvilinear grid from which the total doppler shift may be read off for any hypothetical satellite position; or, alternatively, it is possible to trace out on the grid contours of constant total doppler shift.

To prepare such maps, one ignores for the moment the established geographical coordinates of the site and defines new spherical coordinates relative to the satellite, which will be assumed to be in circular orbit. Assume the site to be at zero degrees latitude and longitude, and let the meridian lines be defined by the intersection of the satellite orbital plane with the earth's surface.

If v is the satellite vector velocity and R_s and R_a are vectors from the center of the earth to the satellite and to the site, the component velocity required is

$$V = \frac{(R_s - R_a)v}{|R_s - R_a|}$$

Using θ and ϕ for latitude and longitude respectively, this reduces to

$$V = \sqrt{gr} \frac{\sin \theta \cos \phi}{\sqrt{\frac{h+r}{r} + \frac{r}{h+r} - 2 \cos \theta \cos \phi}}$$

where:

r = earth's radius,

h = satellite height, and

g = gravitational acceleration corrected for centrifugal effect.

<p>Page Communications Engineers, Inc., Washington, D. C. FINAL REPORT-T-SPACE COMMUNICATIONS TECHNIQUES, April 1963. 178 p. illus. tables, 27 refs., (Proj. 4519; Task 55097) (PCE-R- 9854A; RADC-TDR-63-111) (Contract AF 30(602)-2403)</p> <p>Unclassified report</p> <p>This report describes the expansion of interim simplex space communication facilities at Rome, N. Y., and Trinidad to full duplex for use in com- munication experiments using passive satellites. Objectives of improved tracking accuracy and system gain were achieved by providing a conical scan feed and an optical tracking system at Rome, and new cooled, low-noise doppler tracking re- ceivers at both sites. Full duplex operation, de- (over)</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Antenna systems- Tracking 2. Artificial satellites 3. Communication equipment 4. Communication experiments 5. Communication- Passive satellite 6. Communication system-Space 7. Doppler effect- Measurement 8. Modulation 9. Radar-Distance meas- uring equipment 10. Transmission-Data <p>UNCLASSIFIED</p>
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